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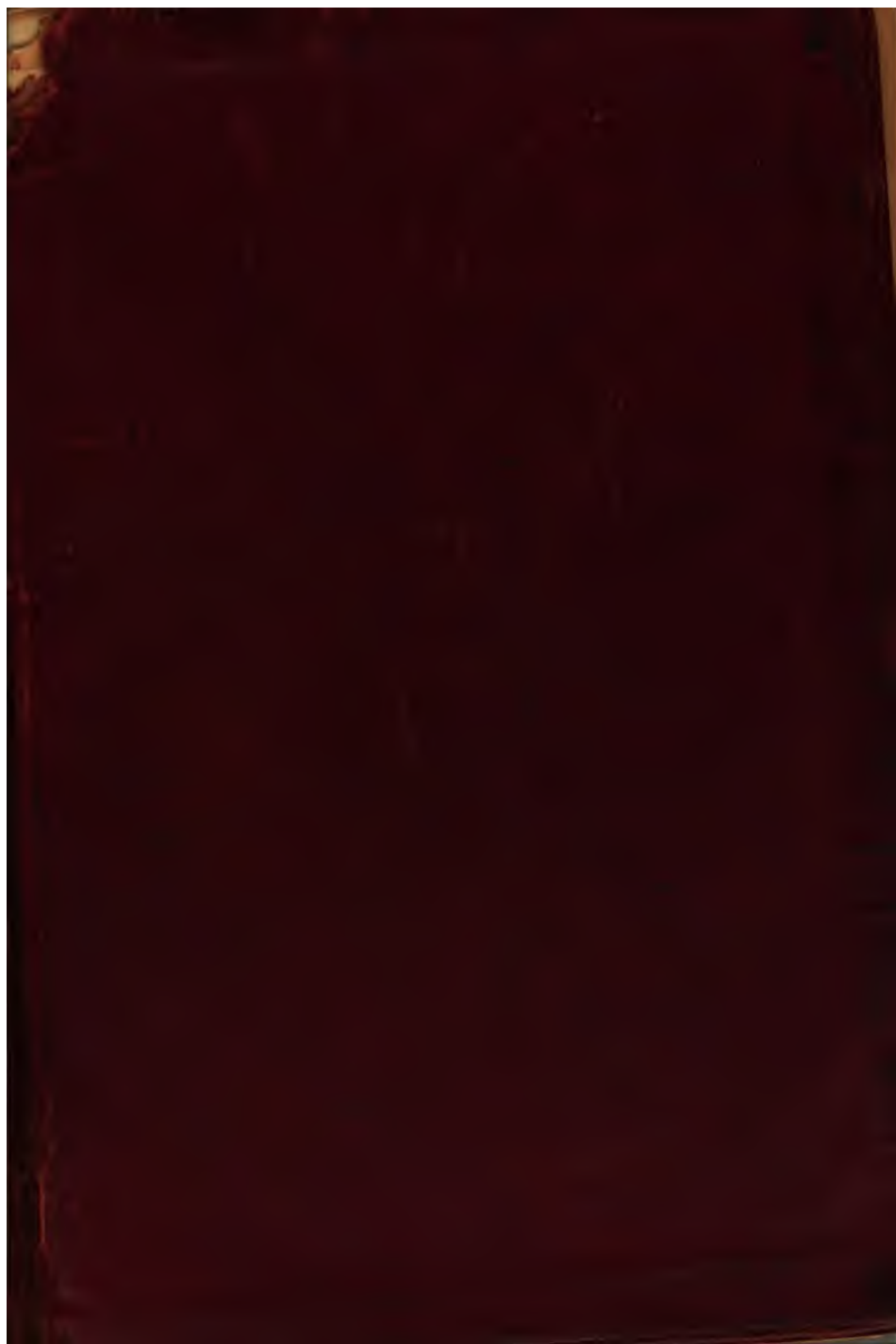
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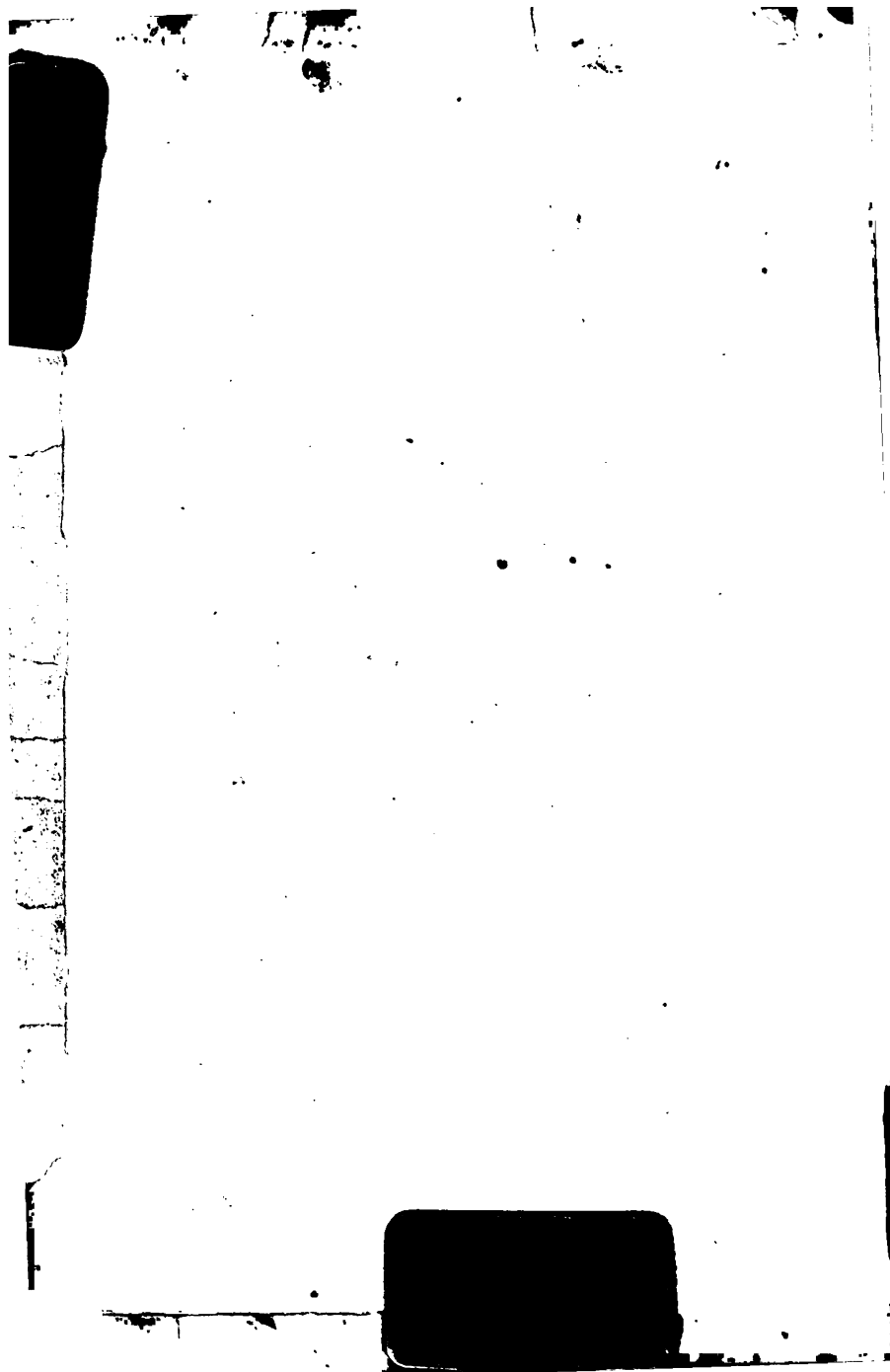




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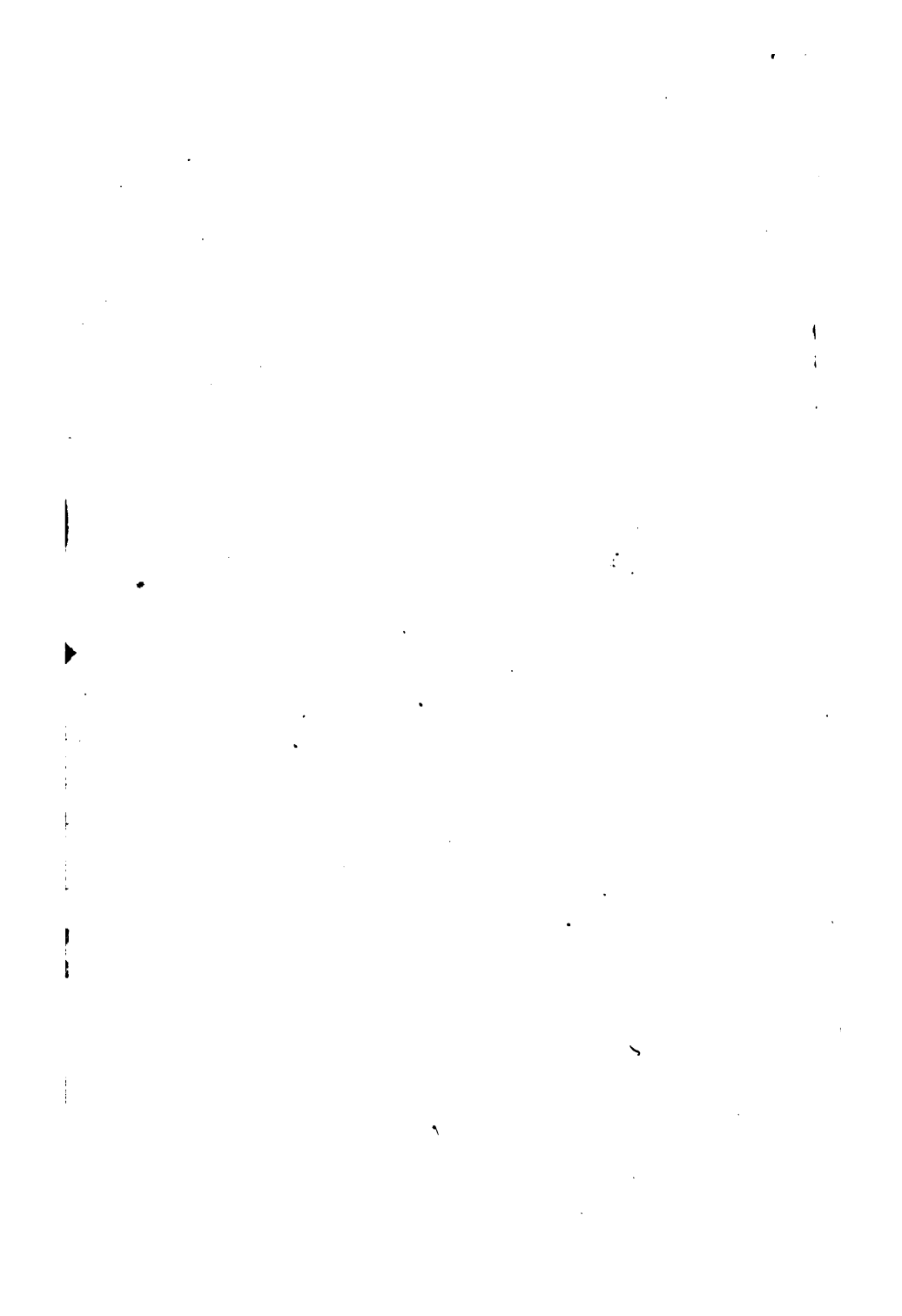
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**INTRODUCTION TO THE  
STUDY OF MINERALS**



Published by the  
**McGraw-Hill Book Company**  
New York

Successors to the Book Departments of the  
McGraw Publishing Company      Hill Publishing Company

Publishers of Books for  
Electrical World      The Engineering and Mining Journal  
Engineering Record      American Machinist  
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Metallurgical and Chemical Engineering      Power

# INTRODUCTION

TO THE

## STUDY OF MINERALS

A COMBINED TEXT-BOOK  
AND  
POCKET MANUAL

BY

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McGRAW-HILL BOOK COMPANY  
239 WEST 39TH STREET, NEW YORK  
6 BOUVERIE STREET, LONDON, E. C.  
1912

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To  
My Parents  
THIS BOOK IS  
GRATEFULLY INSCRIBED



## PREFACE

This work is intended primarily as a text-book for a one-year course in mineralogy. While full enough for class work it is condensed enough for field work. There is decided advantage in using the same book in the field as in the class room and laboratory.

The author's aim has been to produce a well-balanced book covering the whole field of mineralogy as far as is practicable; and one in which the practical methods of identifying minerals, the economic features, and the scientific aspects of mineralogy as a means of correlating hundreds of isolated facts, are all given their proper emphasis. The only way to bring out the important and essential points is to omit the great mass of details which are properly included in the reference books.

Two hundred minerals have been included in the descriptions (Part VI). These have been selected with great care, although the list is necessarily an arbitrary one based upon the writer's experience and judgment. All the common minerals and the more important useful ones are included in the two hundred. Others have been selected for practice in testing and also to give a comprehensive view of the mineral kingdom. In most mineralogical text-books brief descriptions of some of the rare minerals are given. In the writer's opinion this is not advisable, for one needs a full description of a rare mineral in order to identify it.

Of the two hundred minerals given the one hundred most common, in the writer's opinion, are distinguished by larger type in the headings and determinative tables. This selection, like that of the two hundred, is somewhat arbitrary but it undoubtedly includes all the common minerals of the world. In a short course in mineralogy attention may be confined exclusively

to the hundred minerals given in large type. Certain other portions of the book would also be disregarded in a short course.

On the other hand, Sections 16 to 19 of Part I (crystal measurement), Part III (crystal optics), and Part VII (occurrence, origin, and association of minerals) may each serve as the basis for an advanced course in the subject mentioned.

The distinctive features of this book are:

(1) The description of the optical and microscopic properties of crushed fragments, cleavage flakes, and recrystallized products.

(2) Six new determinative tables. These are useful in getting the student familiar with the terms used as well as in the actual determination of minerals.

(3) A numbered list of the occurrences of each mineral, establishing what the author calls *paragenetic varieties*.

(4) A glossary of terms. Synonyms and varieties are usually given in the glossary rather than in the text. In a subject like mineralogy a glossary seems almost a necessity.

In crystallography symmetry has been emphasized and the ideas of hemihedrism, etc., abandoned, though these terms are explained. The thirty-two classes are included for the sake of completeness, but the ten important ones are given more space than the others. Groth's names of the thirty-two classes and von Fedorow's names of forms are used, but the other terms in common use are given in parentheses. The Miller indices have been employed exclusively.

An attempt has been made to give a concise logical presentation of the subject of crystal optics, beginning with the nature of light. Some of the figures may be colored by the student for future reference. This part of the book may serve as an introduction to the study of petrography.

The blowpipe part has been modelled somewhat after Brush-Penfield's excellent manual. A qualitative scheme, especially applicable to minerals in that calcium phosphates, borates, and fluorid are provided for, has been included.

In Part VI the order of the minerals is like that of Dana's *System of Mineralogy* except where there is some special reason for change. The silicates, following Klockmann, Groth, Naumann-Zirkel, and Renard and Stöber, are placed last. The results of analyses of the oxy-salts (excepting silicates) are stated in terms of metals and acid radicals instead of in the usual form of basic and acid anhydrids. This method shows the variation, isomorphic replacement, and molecular ratios as well as the ordinary method, and is not based upon antiquated notions. In stating the results of analyses of acid, basic, and hydrous salts the water percentage is given, as its determination is often of value in the identification of minerals. The analyses are taken mainly from Hintze's *Handbuch* and Dana's *System* (5th and 6th editions).

In the description of minerals (Part VI) a standard form of headings has been used for convenience of reference. Any particular point may easily be found.

Free use has been made of other books, especially those mentioned in the Select Bibliography.

I am greatly indebted to Professor James Perrin Smith for assistance in reading and correcting proof.

AUSTIN F. ROGERS.

STANFORD UNIVERSITY,  
April, 1912.



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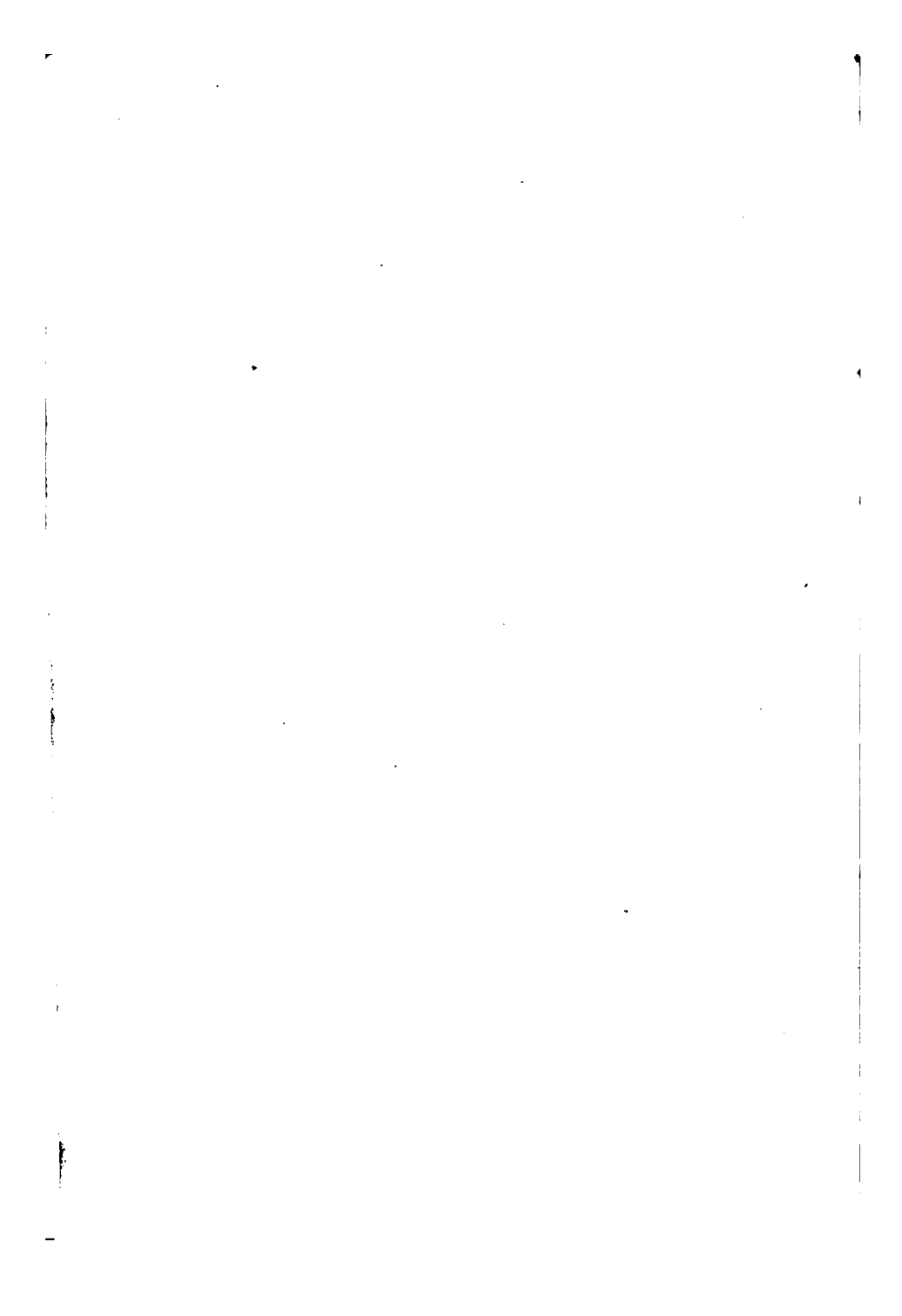
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# SELECT BIBLIOGRAPHY

## PART I

### THE FORM OF MINERALS

- BAUERMANN: *Text-book of Systematic Mineralogy*. Longmans, Green and Co., London, 1889.
- GROTH: *Physikalische Krystallographie*. Wilhelm Engelmann, Leipzig, 1905 (4th edition).
- HILTON: *Mathematical Crystallography and the Theory of Groups of Movements*. Clarendon Press, Oxford, 1903.
- LEWIS: *A Treatise on Crystallography*. Cambridge University Press, 1899.
- LIEBISCH: *Grundriss der Physikalischen Krystallographie*. Veit u. Co., Leipzig, 1896.
- MOSES: *Characters of Crystals*. Van Nostrand, New York, 1899.
- REEKS: *Hints for Crystal Drawing*. Longmans, Green and Co., London, 1908.
- STORY-MASKELYNE: *Crystallography*. Clarendon Press, Oxford, 1895.
- TUTTON: *Crystallography and Practical Crystal Measurement*. Macmillan, London, 1911.
- WILLIAMS: *Elements of Crystallography*. Henry Holt and Co., New York, 1902 (3rd edition).

## PART II

### THE PHYSICAL PROPERTIES OF MINERALS

- GROTH: *Physikalische Krystallographie* (see above).
- LIEBISCH: *Grundriss der Physikalischen Krystallographie* (see above).
- MOSES: *Characters of Crystals* (see above).

## PART III

### THE OPTICAL PROPERTIES OF MINERALS

- DUPARC ET PEARCE: *Traité de Technique Minéralogique et Pétrographique*. (Première Partie.) Veit u. Co., Leipzig, 1907.



- GROTH: *Physikalische Krystallographie* (see above).  
 IDINGS: *Rock Minerals*. Wiley, New York, 1911 (2d edition).  
 LIEBISCH: *Grundriss der Physikalischen Krystallographie* (see above).  
 LUQUER: *Minerals in Rock Sections*. Van Nostrand, New York, 1908 (3rd edition).  
 MOSES: *Characters of Crystals* (see above).  
 WEINSCHENK-CLARK: *Petrographic Methods*. McGraw-Hill Book Co., New York, 1912.  
 WINCHELL AND WINCHELL: *Elements of Optical Mineralogy*. Van Nostrand, New York, 1909.

## PART IV

## THE CHEMICAL PROPERTIES OF MINERALS

- ARZRUNI: *Physikalische Chemie der Krystalle*. Vieweg u. Sohn, Braunschweig, 1893.  
 BRAUNS: *Chemische Mineralogie*. Tauchnitz, Leipzig, 1896.  
 BRUSH-PENFIELD: *Manual of Determinative Mineralogy*. Wiley, New York, 1906 (16th edition).  
 DOELTER: *Physikalisch-Chemische Mineralogie*. Joh. Barth, Leipzig, 1905.  
 GROTH: *Chemische Krystallographie*. Engelmann, Leipzig, 1906 (4 vols.).  
 GROTH-MARSHALL: *Introduction to Chemical Crystallography*. Wiley, New York, 1906.  
 PLATTNER-KOLBECK: *Probierkunst mit dem Lötrohre*. Johann Barth, Leipzig, 1907 (7th edition).  
 PRESCOTT AND JOHNSON: *Qualitative Chemical Analysis*. Van Nostrand, New York, 1908 (6th edition).

## PART V

## THE DETERMINATION OF MINERALS

- BRUSH-PENFIELD: *Manual of Determinative Mineralogy* (see above).  
 KRAUS AND HUNT: *Tables for the Determination of Minerals*. McGraw-Hill Book Co., New York, 1911.

## PART VI

## THE DESCRIPTION OF IMPORTANT MINERALS

- BRAUNS: *Das Mineral Reich*. Fritz Lehmann, Stuttgart, 1903.  
 DANA: *System of Mineralogy*. Wiley, New York, 1892 (6th edition).  
 1st appendix, 1899. 2nd appendix, 1909.

- GROTH: *Tabellarische Uebersicht der Mineralien*. Vieweg u. Sohn, Braunschweig, 1898 (4th edition).
- FOOTE: *Complete Mineral Catalog*. Foote Mineral Co., Philadelphia, 1909.
- HINTZE: *Handbuch der Mineralogie*, Veit u. Co., Leipzig, 1897. II Band. (I Band, not complete).
- MIERS: *Mineralogy*. Macmillan, London, 1902.
- NAUMANN-ZIRKEL: *Elemente der Mineralogie*. Engelmann, Leipzig, 1901 (14th edition).
- ROSENBUSCH-WÜLFING: *Mikroskopische Physiographie der petrographisch wichtigen Mineralien*. E. Schweizerbartsche Verlagshandlung, Stuttgart, 1905.

## PART VII

## THE OCCURRENCE, ASSOCIATION, AND ORIGIN OF MINERALS

- BECK-WEED: *The Nature of Ore Deposits*. McGraw-Hill Book Co., New York, 1911 (2nd edition).
- BRAUNS: *Chemische Mineralogie* (see above).
- CLARKE: *The Data of Geochemistry*. U. S. Geological Survey, Washington, 1908 (Bulletin 330).
- GEIKIE, JAMES: *Structural and Field Geology*. Oliver and Boyd, Edinburgh, 1908 (2nd edition).
- KEMP: *Handbook of Rocks*. Van Nostrand, New York, 1911 (5th edition).
- KLOCKMANN: *Lehrbuch der Mineralogie*. Ferd. Enke, Stuttgart, 1907 (4th edition).
- LACROIX: *Mineralogie de la France et de ses Colonies*. Librairie Polytechnique, Paris, 1893-1910 (4 vols).
- MEUNIER: *Les Méthodes de Synthèse en Mineralogie*. Librairie Polytechnique, Paris, 1891.
- PIRSSON: *Rocks and Rock-Minerals*. Wiley, New York, 1908.

## PART VIII

## THE USES OF MINERALS

- BAUER: *Edelsteinkunde*, Tauchnitz Leipzig, 1896.
- BEYSLAG-KRUSCH-VOGT: *Die Lagerstätten der nutzbaren Mineralien und Gesteine*. Ferd. Enke, Stuttgart, 1909.
- BRANNER: *Syllabus of Economic Geology*. J. C. Branner, Stanford University, Cal., 1911 (3rd edition).
- FARRINGTON: *Gems and Gem Minerals*. A. W. Mumford, Chicago, 1903.

KUNZ: *Gems and Precious Stones of North America*. Scientific Publishing Co., New York, 1892 (2nd edition).

MERRILL: *The Non-Metallic Minerals*. Wiley, New York, 1905.

MOSES AND PARSONS: *Elements of Mineralogy, Crystallography, and Blow-pipe Analysis*. Van Nostrand, New York, 1909 (4th edition).

PENFIELD: *Tables of Minerals*. Wiley, New York, 1907 (2nd edition).

RIES: *Economic Geology*. Macmillan, New York, 1910 (3rd edition).

*The Mineral Industry*. Published annually since 1892 by the McGraw-Hill Book Co., New York.

*The Mineral Resources of the United States*. Published annually since 1883 by the U. S. Geological Survey, Washington.

## INTRODUCTION

Minerals are those parts of the earth's crust which have a definite chemical composition. Such substances as oil, coal, clay, and soil are not considered as minerals, for they do not have a definite chemical composition. Rocks such as granite, limestone, sandstone, etc., are mixtures of minerals though, in a few cases, they are composed of a single mineral. Materials of organic origin such as amber, coal, and pearls are by common consent excluded, but petrifications formed by the replacement of organisms by minerals are included.

About a thousand definite kinds of minerals have been discovered, though many of them are very rare and are confined to one or two localities. It is with the two hundred more common and important minerals that we are especially concerned.

The purpose of this book is to explain and record the prominent characters of minerals so that one may learn to recognize them by sight or by simple physical and chemical tests and also to discuss their uses and their manner of occurrence.

Minerals, like plants and animals, have characteristic forms, though they are not the result of growth in the ordinary sense of the term. Nearly all minerals under favorable conditions are found in characteristic geometric forms called crystals, which are often very regular and beautiful. They have very appropriately been called "flowers of the earth." Though often seemingly unlimited in variety, the crystals of a given mineral are all derivatives of a simple type.

Minerals do not, however, always occur in distinct isolated

crystals. They usually consist of a confused aggregate of grains, fibers, or plates. Such an aggregate is said to be crystalline for the separate particles are crystals in one sense of the word, that is, they have the internal structure of crystals. After all the regular arrangement of its molecules is the characteristic feature of a crystal, the external form being simply an outward expression of the internal structure.

In crystals the cohesion between particles varies with the direction and hence minerals usually break more easily in certain directions than in others. This property is known as cleavage and is useful in determining minerals.

The subject treating of action of light, especially polarized light, upon transparent crystals constitutes crystal optics, or if limited to minerals, optical mineralogy. The secrets of the rocks revealed by the polarizing microscope are not only wonderful, but are also useful in the determination of minerals.

One of the most fundamental properties of minerals is the chemical composition and hence a knowledge of chemistry is indispensable in the study of minerals. For the sight recognition of minerals various physical characters are important, but for identification chemical and blowpipe tests are often necessary. The blowpipe, especially, is a great aid in rapid testing. It can be used to advantage because one usually knows what to test for and can readily confirm his sight determinations.

The economic side of mineralogy will appeal to many on account of its practical application. The history of mineralogy began with the discovery of metallic ores and other useful minerals and the study of mineralogy as a pure science has been kept alive principally because of the aid it has given in the development of mineral resources.

Perhaps the most fascinating branch of mineralogy is that dealing with the occurrence, association, and origin of minerals. While necessarily a thoroughly scientific subject pursued for its own sake by the specialist, its use in determining the origin of ores will give it a standing which it otherwise might not have.

# PART I

## THE FORM OF MINERALS

### 1. THE GENERAL PROPERTIES OF CRYSTALS

In beginning the study of crystallography the student's attention may be directed to crystals of the common minerals such as calcite (Figs. 151-162), quartz (Figs. 435-438), pyrite (Figs. 198-205), gypsum (Figs. 102-105), and orthoclase (Figs. 90-93). Then for the time neglecting how they were formed and what they are composed of, their form or geometrical properties may be considered.

Crystals are solids bounded by flat, more or less smooth, surfaces called **faces**. Intersections of two faces are called **edges**, and intersections of three or more faces are called **vertices**. The number of faces plus the number of vertices is equal to the number of edges plus two. ( $F + V = E + 2$ ). The faces of crystals vary greatly in number, in shape, and in position. On many crystals it will be noticed that there are several kinds of faces. All the faces of one kind on a crystal constitute a **form**. For example in Fig. 5, the top and bottom six-sided faces constitute one form, and the six rectangular faces another form. Some crystals have only a single form, but most of them are **combinations** of two or more forms. It is the great possible number of combinations that gives the variety to crystals, for there is no limit to the number of forms on a crystal.

The angles on any crystal are the plane angles of the faces, the interfacial or dihedral angles over the edges, and the solid or polyhedral angles at the vertices. On account of the difficulty of accurate measurement the plane angles, though characteristic, are

little used. The measurement of interfacial angles is the starting-point in the description and determination of crystals. An **interfacial angle** (dihedral angle of geometry) is defined by the plane angle formed by cutting a plane normal to the intersection edge of the two faces. It will be noticed that there are two possible angles to measure, an internal and an external or supplement angle. For various reasons the supplement angle is the one used

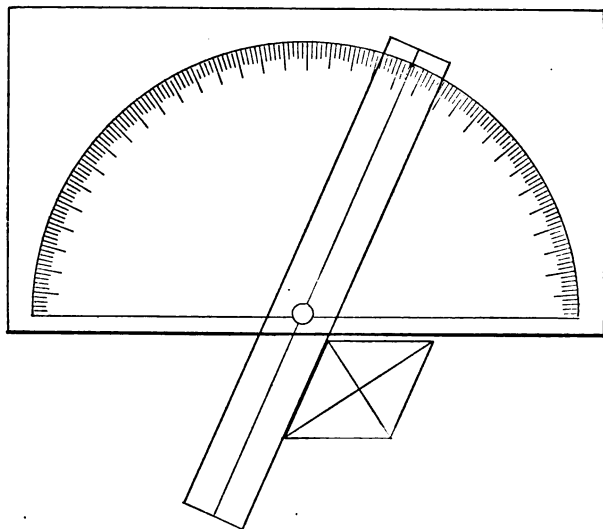


FIG. 1.—Contact goniometer.

in crystallography. In a hexagonal prism, for example, the interfacial angle is read  $60^\circ$  instead of  $120^\circ$ . The interfacial angle may be measured approximately by means of a **contact goniometer**, which, in the simplest type, consists of a semicircular cardboard protractor provided with a celluloid arm (Fig. 1). The plane of the protractor is placed perpendicular to the intersection edge. One face of the crystal is brought in contact with the arm and the protractor is revolved until the other face is parallel to, but not quite in contact with, it.

One of the most striking and important properties of crystals is the recurrence of the faces, edges, and vertices. This property of recurrence is known as **symmetry**. It varies for different kinds of crystals, and is the basis for the classification of crystals.

The arrangement of faces in belts of planes with parallel intersection edges called **zones** is another notable feature of crystals.

On looking over a number of crystals one might fail to see any order, system, or regularity so great is their variety, and might decide that crystals are fortuitous solids. But such is not the case, for between the faces, angles, and zones of crystals there exist exact mathematical relations. Given the angles between a few faces of a crystal, the angles between any two of the many crystal faces possible may be calculated. Crystal faces intersect only at certain definite angles. A facet cut at random on a crystal is not a crystal face, for the faces are the result of a definite internal structure.

The practical importance of crystallography lies in the fact that a given mineral or artificially prepared compound occurs in crystals characteristic of that substance, and hence the crystal form may often be used in the determination of the substance.

## 2. THE SYMMETRY OF CRYSTALS

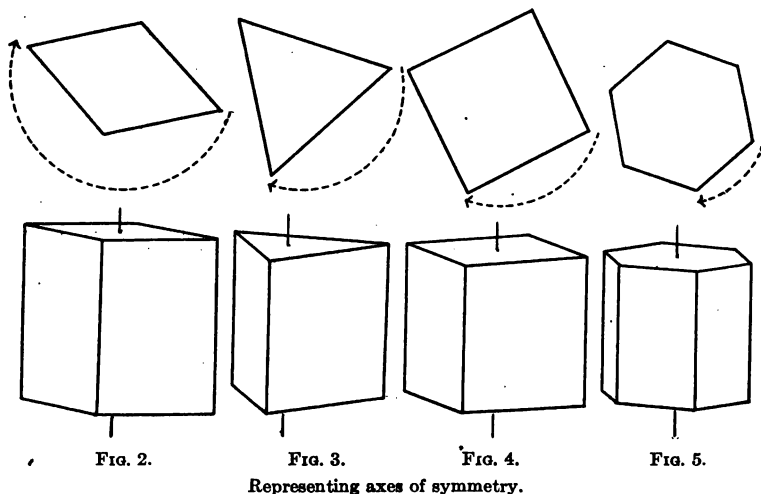
The repetition of the faces, interfacial angles, and vertices of crystals in accordance with some fixed law is called **symmetry**. Symmetry is perhaps the most important property of crystals, for among natural objects it is a property peculiar to crystals, and besides furnishes the basis for the classification of crystals.

The symmetry of a crystal may be defined by the operations necessary to bring it into coincidence with its original position. The symmetry operations are rotation about an axis, reflection in a plane, and a combination of rotation with reflection (rotatory-reflection).

If a solid can be revolved about some line through its center so that similar faces recur a certain number of times in a complete



revolution, that line is called an **axis of symmetry** (denoted by **A**). In crystals the period of the axis or the number of times of recurrence is either two (2), three (3), four (4), or six (6). An axis about which similar faces recur every  $180^\circ$  is said to be a **two-fold axis** ( $A_2$ ); every  $120^\circ$ , a **three-fold axis** ( $A_3$ ); every  $90^\circ$ , a **four-fold axis** ( $A_4$ ); and every  $60^\circ$ , a **six-fold axis** ( $A_6$ ). Figs. 2, 3, 4, and 5 illustrate these various axes of symmetry. The vertical



lines through the center are the axes of symmetry. The plane figures above are plans showing the amount of rotation necessary to bring the figures into self-coincidence.

A plane that divides a solid into two parts so that similar faces occur on opposite sides of the plane is called a **plane of symmetry** (denoted by **P**). Fig. 6 represents an orthoclase crystal in which the shaded area is a plane of symmetry. The faces are either perpendicular to this plane, or occur in pairs, one on each side of it. A crystal may have several planes of symmetry. A cube, for example, has nine, three perpendicular to the faces and six through the edges.

The recurrence of similar faces by rotation about an axis combined with reflection in a plane is called **composite symmetry** (denoted by  $\mathcal{A}$ ). The period of the axis may be 2, 4, or 6, but never 3. The particular operation denoted by  $\mathcal{A}_2$  is called **inversion**. As may be seen from Fig. 7 the front part of the crystal if revolved  $180^\circ$  becomes the reflection of the rear part (dotted lines). A solid which is brought into self-coincidence by inversion is said to have a **center of symmetry** (denoted by C), for a line drawn from any point through the center encounters an exactly similar point on the opposite side. Fig. 7 represents a crystal

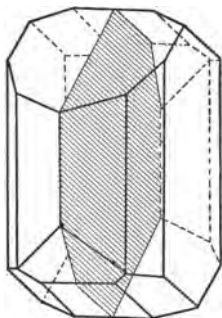


FIG. 6.—Plane of symmetry.

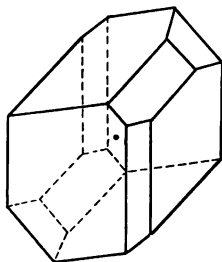


FIG. 7.—Center of symmetry.

of axinite with a center of symmetry. Every face has a similar parallel face on the opposite side of the crystal. This is the easiest test for a center of symmetry. In Fig. 8 the vertical line is an axis of four-fold composite symmetry, for the upper part of the crystal revolved  $90^\circ$  is a reflection of the lower part. Similarly the vertical line in Fig. 9 is an axis of six-fold composite symmetry.

Axis, plane, and composite axis with plane are collectively known as **elements of symmetry**. In crystals the elements of symmetry are combined in various ways. With the limitation imposed by the rationality of the indices, or with the assumption of a crystal structure made up of particles at small, finite dis-

tances apart only axes of 2-, 3-, 4-, and 6-fold symmetry are possible, and in fact no other axes of symmetry have ever been found in crystals. Various methods of combining the axes of symmetry with each other, and with planes of symmetry, lead to the result that only thirty-two kinds of symmetry are possible among crystals. These thirty-two combinations of symmetry elements constitute the **thirty-two crystal classes**.

In the above discussion the term similar faces has been used so often that an explanation is necessary. By similar faces are

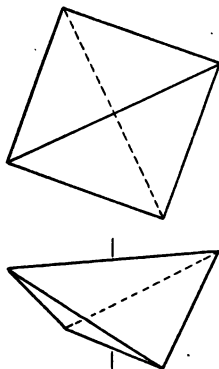


FIG. 8.— $P_4$ .

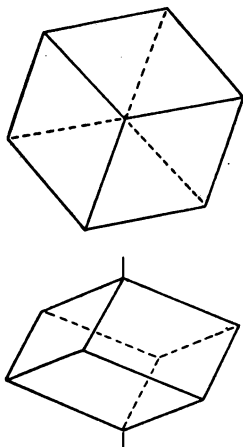


FIG. 9.— $P_6$ .

meant faces which are more or less alike in shape, size, and appearance. On crystals which have been formed quietly without disturbing influences similar faces have the same size and shape. But on account of various external influences similar faces are rarely *exactly* of the same size and shape. The effect of external influences may be illustrated by alum which crystallizes in octahedrons. Alum crystallizing on the bottom of a beaker will form in more or less flattened octahedrons like Fig. 11, while if it crystallizes about a weighted string suspended in the solution, the crystals will be more or less perfect octahedrons like Fig. 10.

The irregularity in the size and shape of similar faces is one difficulty in the study of crystals. While the faces may vary the angles are quite constant, as is expressed in the law of constancy

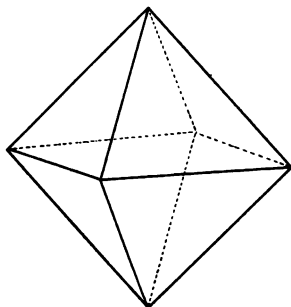


FIG. 10.

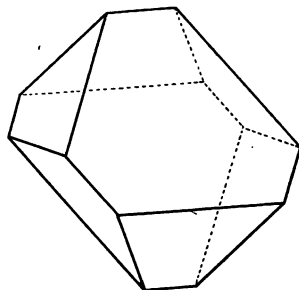


FIG.—11.

Alum crystals.

of interfacial angles: **"In all crystals of the same substance the angles between corresponding faces are constant."** So that for many crystals the interfacial angles must be measured in order to determine the symmetry. Thus the crystals represented in cross-section by Figs. 12, 13, 14 are bounded by hexagonal prisms

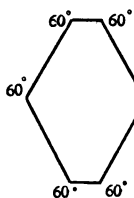


FIG. 12.

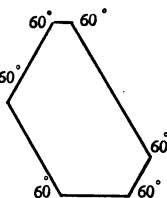


FIG. 13.

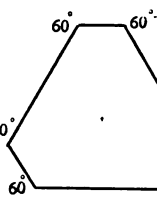


FIG. 14.

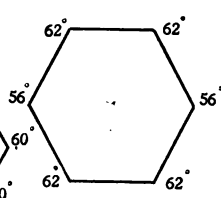


FIG. 15.

and have an axis of six-fold symmetry if the interfacial angles are all  $60^\circ$ . On the other hand, the crystal represented in cross-section by Fig. 15, though apparently a hexagonal prism, is a combination of two forms (a rhombic prism and a pinacoid), and

has an axis of two-fold symmetry because the interfacial angles are  $62^\circ$  and  $56^\circ$ .

Another property of crystals used in determining symmetry is the physical character of the faces. So that crystallography is by no means merely a branch of geometry. Similar faces are those with the same luster, the same kind of striations, pits, or other markings. Geometrically a cube has nine planes of symmetry, three parallel to the cube faces, and six through the cube edges, but a cube of pyrite with striations like those of Fig. 16 has only three planes (those parallel to the cube faces). A crys-

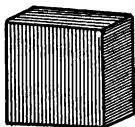


FIG. 16.  
Pyrite.

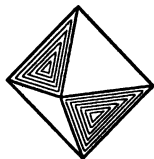


FIG. 17.  
Sphaferite.

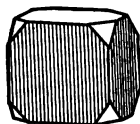


FIG. 18.  
Apophyllite.

tal of sphaferite represented by Fig. 17 is geometrically an octahedron, but crystallographically it is a combination of two tetrahedrons, one with smooth faces, the other with striated faces. Fig. 18 illustrates another good example of this kind. Apophyllite occurs in crystals which are apparently cubes modified by the octahedron. Close examination, however, shows that the side faces are striated and have a vitreous luster, while the top and bottom faces are smooth and have a pearly luster. The forms, then, are a pinacoid and square prism instead of a cube. The apparent octahedron is in reality a tetragonal bipyramid or a double-ended square pyramid.

### 3. THE FORMS OF CRYSTALS

The similar faces of a crystal constitute a **form**, form being used here in a special technical sense. Similarity of faces on many crystals may be observed at a glance, but for others not only

careful examination and measurement, but also etching with some solvent is necessary. Similar faces will have the same kind of etch-figures (see page 108).

There are many kinds of forms. The most logical method is to name the forms according to their shape, regardless of their position on the crystal. A single face is a **pedion** (Fig. 19). Two

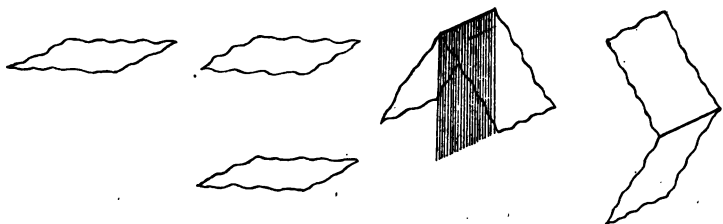


FIG. 19.—Pedion. FIG. 20.—Pinacoid. FIG. 21.—Dome. FIG. 22.—Sphenoid.

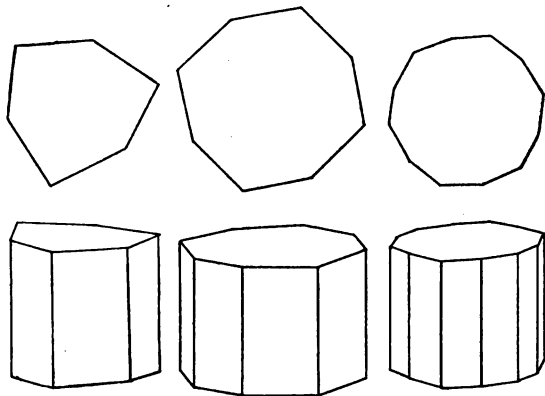
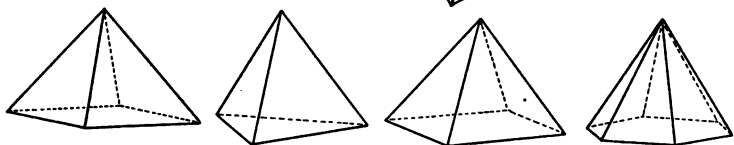
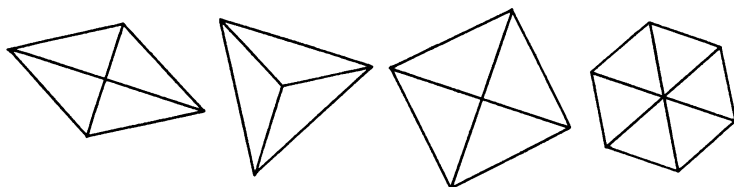


FIG. 23. FIG. 24. FIG. 25.  
Ditrigonal prism. Ditetragonal prism. Dihexagonal prism.

parallel faces constitute a **pinacoid** (from the Greek word for a board), Fig. 20. Two non-parallel faces are called a **dome** (Latin word for house) Fig. 21, if astride a plane of symmetry, but a **sphenoid** (Greek word for wedge), Fig. 22, if not astride a plane of symmetry.

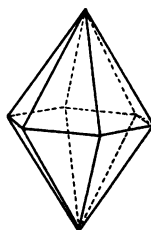
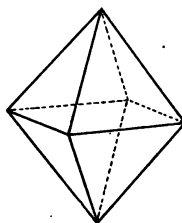
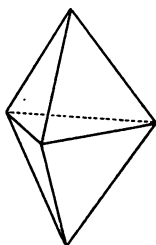
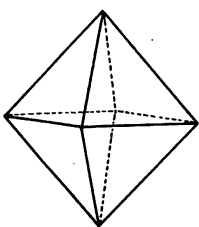


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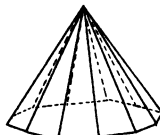
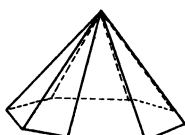
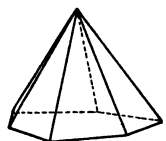
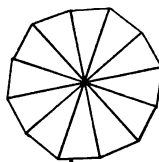
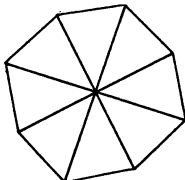
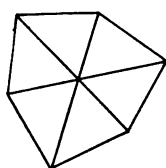
33

Rhombic.

Trigonal.

Tetragonal.

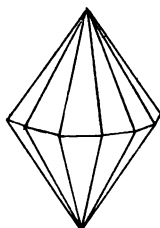
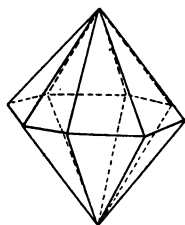
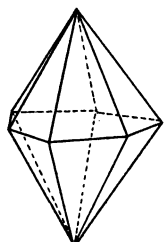
Hexagonal



34

35

36



37

38

39

Ditrigonal.

Ditetragonal.

Dihexagonal.

FIGS. 26-39.—Pyramids and bipyramids.

Next we have three, four, six, eight, or twelve similar faces in one zone. These are called **prisms** and are distinguished according to their cross-section as trigonal (Fig. 2), rhombic (Fig. 3), tetragonal (Fig. 4), hexagonal (Fig. 5), ditrigonal (Fig. 23), ditetragonal (Fig. 24), and dihexagonal (Fig. 25). **Pyramids** are similar

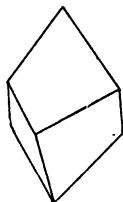


FIG. 40.

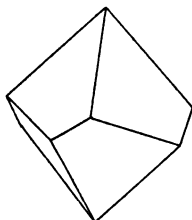


FIG. 41.

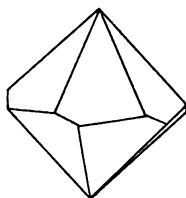


FIG. 42.

faces intersecting in a point. They are defined by the shape of the cross-section just as the prisms are. See Figs. 26 to 29, and 34 to 36. **Bipyramids**, geometrically considered, are two pyramids placed end to end. They are defined by cross-section just as prisms and pyramids are. See Figs. 30 to 33 and 37 to 39.

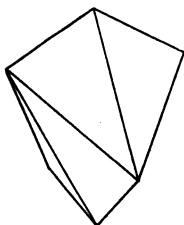


FIG. 43.

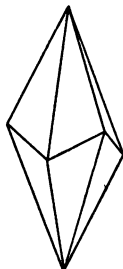


FIG. 44.

**Trapezohedrons** are double-ended forms with the symmetry  $A_n \cdot nA_2$ . They are distinguished as trigonal (Fig. 40), tetragonal (Fig. 41), or hexagonal (Fig. 42), according to the cross-section. **Bisphenoids** are forms consisting apparently of two sphenoids placed together symmetrically. They are called rhom-

bic (Fig. 48), or tetragonal (Fig. 8), according to cross-section. A **rhombohedron** is a form consisting of six rhombic faces, three at each end of a six-fold axis of composite symmetry (Fig. 9). It is like a cube distorted along one of its diagonals. **Scalenohedrons** are double-ended forms consisting of scalene triangular



faces meeting in zigzag edges. They are distinguished by their cross-section as ditrigonal (Fig. 43), and ditetragonal (Fig. 44).

There are fifteen more kinds of forms which are restricted to the isometric system. Some of these such as cube, octahedron, and tetrahedron are simple, but as most of them are complicated, their description is deferred until the isometric system is taken up.

Of the above mentioned forms, the pyramids, prisms, pinacoid, dome, sphenoid, and pedion cannot occur by themselves; and for that reason are called **open forms**. All the others are called **closed forms** for they enclose space of themselves.

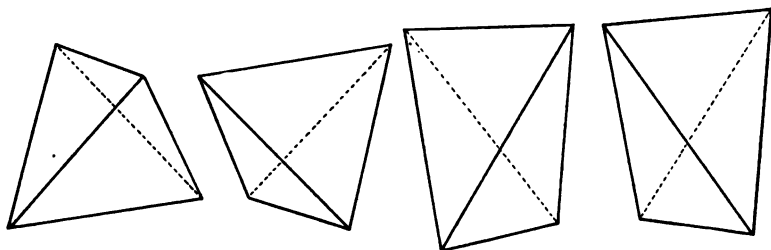


FIG. 45.

Congruent tetrahedra.

FIG. 46.

FIG. 47.

Enantiomorphous rhombic bisphenoids.

FIG. 48.

Two forms are said to be **congruent** if one of them may be made coincident with the other by rotation. For example, the tetrahedra of Figs. 45 and 46 are congruent. Two forms are said to be **enantiomorphous** if they are non-superposable and the mirror-image of each other. The rhombic bisphenoids of Figs. 47 and 48 are enantiomorphous. Two forms are said to be **complementary** when their combination is *geometrically* indistinguishable from another kind of form. For example, the two tetrahedra of Fig. 17 are complementary, for geometrically they form an octahedron.

Another method of naming forms that is in general use is based upon the position of faces with respect to the axes of reference (*q.v.*). Thus a *pinacoid* is defined as a form that cuts one

axis and is parallel to the other two. A *prism* is defined as a form that is parallel to the vertical axis and cuts the other two. A form that is parallel to one of the lateral axes and cuts the other two is a *dome*. A form that cuts all three axes is in general called a *pyramid*. A pyramid developed at only one end of the vertical axes is known as a *hemimorphic pyramid*. In the monoclinic and triclinic systems the names of forms are based upon the analogy of these systems with that of the orthorhombic. For example, in the monoclinic system  $\{hkl\}$  is called a *hemi-pyramid* because there are one-half as many faces as in the corresponding form of the orthorhombic system while  $\{hkl\}$  in the triclinic system is a *tetarto-pyramid*, there being but two faces instead of eight. In the monoclinic system  $\{h0l\}$  is a *hemi-dome* because  $\{h0l\}$  in the orthorhombic system is a dome. In the triclinic system  $\{hk0\}$  is a *hemi-prism* consisting of two opposite parallel faces instead of the four faces of the prism  $\{hk0\}$  of the orthorhombic system. But as said before the logical names of forms are based upon their shape and not upon their position on the crystal.

#### 4. THE SYMBOLS OF CRYSTAL FACES

Crystal measurement proves that exact mathematical relations exist between crystal faces. To make use of this fact the position of crystal faces is defined by the method of analytic geometry, which consists in referring them to three (in one case, four) suitably chosen coördinate axes passing through the center of the crystal. These axes are called **axes of reference** to distinguish them from axes of symmetry. The selection of these axes is more or less arbitrary, but they are chosen so as to yield the simplest relations possible. They are therefore lines parallel to prominent edges, which are usually either axes of symmetry or normals to planes of symmetry.

Any face may be defined by its intercepts on the axes of reference. In Fig. 49 the axes are the dot-and-dash lines OX, OY, and OZ intersecting at the origin, O. The intercepts of the plane

ABC (extension of the face  $m$ ) are OA, OB, and OC. The intercepts of the plane HKL (extension of the face  $n$ ) are OH, OK, and OL.

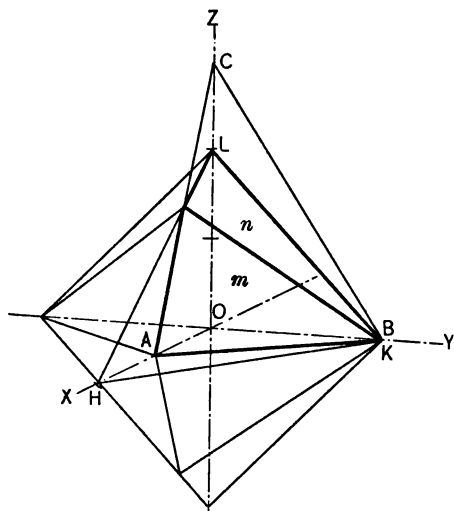


FIG. 49.

Now it has been found that the ratios OA:OH, OB:OK, and OC:OL on any one crystal are *usually simple rational numbers* such as 1:3, 1:2, 1:1, 2:1, 4:1, etc., while the ratios OA:OB:OC and OH:OK:OL are, in general, irrational. In Fig. 49, the ratios OA:OH = 1:2, OB:OK = 1:1, OC:OL = 3:2.

In the case of the mineral barite the relative intercepts of some of the faces are as follows (the letters referring to Fig. 50):

Letter	Intercepts	Weiss symbols	Miller indices
$m$	0.815: 1: $\infty$	$a: b: \infty c$	110
$a$	0.815: $\infty: \infty$	$a: \infty b: \infty c$	100
$u$	0.815: $\infty: 1.313$	$a: \infty b: c$	101
$d$	0.815: $\infty: 0.656$	$a: \infty b: \frac{1}{2}c$	102
$l$	0.815: $\infty: 0.328$	$a: \infty b: \frac{1}{4}c$	104
$c$	$\infty: \infty: 1.313$	$\infty a: \infty b: c$	001
$o$	$\infty: 1: 1.313$	$\infty a: b: c$	011
$y$	0.815: 0.5: 0.656	$a: \frac{1}{2} b: \frac{1}{2}c$	122
$z$	0.815: 1: 1.313	$a: b: c$	111

The expressions for the intercepts are cumbersome. A simple method of notation is suggested by the fact that these values for different faces are in the ratio of simple rational numbers. We may select the expression for one of these faces

as a standard and represent the other faces by the simple numbers. In barite the face  $z$  with the intercepts  $0.815:1:1.313$  has been taken as the **unit face**. This establishes the **axial ratio** as  $a:b:c=0.815:1:1.313$ .

The symbols for the other faces may be written as in the second column. These are called the **Weiss symbols** from the name of the German crystallographer who devised them (1818). As the order  $a, b, c$  is always understood these letters may be omitted and as infinity gives trouble in mathematical calculations, the reciprocal values of the ratios may be used. We then have the symbols of the third column. If  $OA:OB:OC$  are the intercepts of a unit face the symbol of another face with the intercepts  $OH:OK:OL$  is  $hkl$  in the

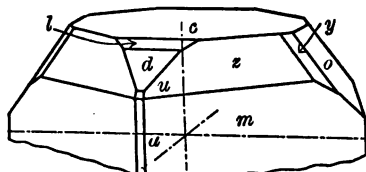


FIG. 50.—Barite crystal.

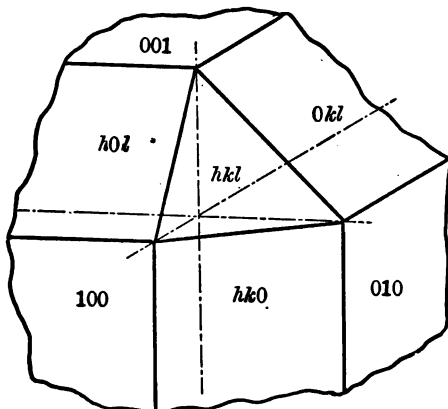


FIG. 51.—The seven type faces.

expression  $\frac{OA}{OH} : \frac{OB}{OK} : \frac{OC}{OL} = h:k:l$ . The three simplest whole numbers that express this ratio are called the **Miller indices**, as Miller, formerly professor of mineralogy at the University of Cambridge, was the first to make extensive use of this method.

The symbol  $hkl$  is an algebraic expression standing for certain numbers and so is called a **type symbol**. Besides a face that cuts all three axes of reference we have the faces  $hko$ ,  $h0l$ , and  $0kl$  each of which cuts two axes and is parallel to the third and  $h00$  (100),  $0k0$  (010), and  $00l$  (001) each of which cuts one axis and is

parallel to the other two. These constitute the seven so-called type symbols and are represented in Fig. 51. (Fig. 557, page 413, represents an olivine crystal with seven actual type forms.) As in analytic geometry the front, right, and top ends of the axes are considered as positive, while the back, left, and bottom ends are considered as negative. A negative index is indicated by a line over the letter. There are eight planes which cut the axes at the same relative distances, but in different octants. They are  $hkl$ ,  $\bar{h}kl$ ,  $h\bar{k}l$ ,  $hkl$ ,  $\bar{h}\bar{k}l$ ,  $\bar{h}kl$ , and  $h\bar{k}l$ . These symbols as just

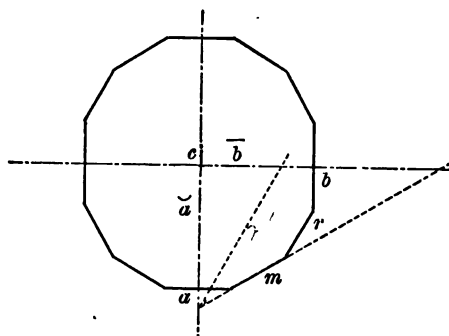


Fig. 52.—Graphic determination of indices.

written are **face-symbols**. The symbol of one face  $hkl$  may be taken to represent the form. The **form-symbol** is often written with brackets  $\{hkl\}$  to distinguish it from a face-symbol  $hkl$  or  $(hkl)$ . In order to determine the type symbol it is only necessary to write the indices  $h, k, l$ , in the order of the axes  $a, b, c$ , substituting 0 when the face is parallel to an axis. In writing type symbols the reciprocal idea may be disregarded.

The determination of the symbol involves calculation by means of trigonometry, or the corresponding graphical solutions. A simple case is illustrated by Fig. 52. Here we have a rectangular zone of  $(hk0)$  faces,  $a, m, r, b$ , where  $a$  is  $(100)$  and  $b$  is  $(010)$ , the axes of reference being parallel to these two faces. Assuming  $m$  to be  $(110)$  the problem is to determine the symbol of  $r$ . Move  $r$  parallel to itself until  $r$  and  $m$  intersect the  $a$ -axis at a common point. Then the intercept of  $r$  on the  $b$ -axis, it may be seen, is one-third of that of  $m$ . The intercepts of the  $r$ -face are  $1a : \frac{1}{3}b : \infty c$  or  $\frac{1}{3}a : \frac{1}{3}b : \frac{1}{3}c$ . The Miller indices are  $(130)$  (read one, three, zero).

The law of the rationality of the indices, which has been established by the measurement of thousands of crystals, is the foundation of geometrical crystallography. The axial ratio for a given substance having once been established by a unit face, all the other possible faces may be predicted, for their interfacial angles can be calculated by the formulæ of plane and spherical trigonometry.

Why the symbol (111), in the case of barite for example, does not represent a face that cuts the three axes at equal lengths is one of the most difficult points for the student of crystallography to comprehend. Several illustrations may clear up this point. Take two cities laid out according to different plans. Say in one, the blocks are 475 feet long and 325 feet wide, and in the other 650 feet long and 300 feet wide. A pedestrian on inquiring about a certain building in each place might be directed to go two blocks north and three blocks east. Yet the actual distance for him to walk in the two cities would be different for the lengths of the blocks are different. The lengths of the blocks are on record in the city engineer's office, but the pedestrian is not directly concerned with them, but with the directions given him. The axial ratios for crystals are established and on record in reference books, but in the description of the various crystal faces and forms use is always made of Miller indices or other symbols rather than of the actual intercepts of the faces.

Another analogous case that will appeal to the student of chemistry is the law of definite proportions and the law of multiple proportions. In the chemical formulæ,  $\text{CuO}$  and  $\text{Cu}_2\text{O}$ ,  $\text{CuO}$  means that there are 63.6 parts (by weight) of copper and 16 parts of oxygen, while  $\text{Cu}_2\text{O}$  means that there are 127.2 ( $2 \times 63.6$ ) parts of copper and 16 parts of oxygen. The atomic weights have been determined and are given in tables, but they are not expressed in chemical formulæ.

In order that the symbols may be as simple as possible it has been found convenient to have six kinds of axes of reference, to some one of which the crystals of every known substance are

referred. The axes of reference differ in relative length and also in their inclinations to each other. In one case four axes are used instead of three. The kinds of axes of reference serve as a basis for the crystal systems, which are defined in the next section.

## 5. THE CLASSIFICATION OF CRYSTALS

The modern classification of crystals is based upon symmetry. Only axes of 2-fold, 3-fold, 4-fold, and 6-fold symmetry have ever been found on crystals. With this limitation it may be demonstrated that only thirty-two combinations of symmetry elements are possible. A rigid mathematical proof will not be given here, but the following table shows the relation between the various combinations. A single axis alone (singular axis) gives the five classes of row 1. For the sake of completeness the axis of one-fold symmetry ( $A_1$ ) is included.

1	$A_1$	$A_2$	$A_3$	$A_4$	$A_6$
2	$(A_1 \cdot 1A_2)$	$A_2 \cdot 2A_2$	$A_3 \cdot 3A_2$	$A_4 \cdot 4A_2$	$A_6 \cdot 6A_2$
3	$A_1 \cdot P$	$A_2 \cdot P$	$A_3 \cdot P$	$A_4 \cdot P$	$A_6 \cdot P$
4	$(A_1 \cdot 1P)$	$A_2 \cdot 2P$	$A_3 \cdot 3P$	$A_4 \cdot 4P$	$A_6 \cdot 6P$
5	$(A_1 \cdot A_2 \cdot 2P)$	$A_2 \cdot 2A_2 \cdot 3P$	$A_3 \cdot 3A_2 \cdot 4P$	$A_4 \cdot 4A_2 \cdot 5P$	$A_6 \cdot 6A_2 \cdot 7P$
6		$P_2$		$P_4$	$P_6$
7				$P_4 \cdot 2A_2 \cdot 2P$	$P_6 \cdot 3A_2 \cdot 3P$

If this axis has combined with it an axis of 2-fold symmetry, there must be as many of these axes as the period of the singular axis indicates. We then have the five classes of row 2, but  $A_1 \cdot 1A_2$  is the same as  $A_2$ . The singular axis of row 1 may have a

plane of symmetry perpendicular to it which gives the five classes of row 3. If the planes of symmetry are through the singular axis there must be  $n$  of them for  $A_n$ . Thus we have row 4, but  $A_1 \cdot 1P$  is the same as  $A_1 \cdot P$ . Combining the first four rows in various ways we have row 5. Rows 6 and 7 represent axes of composite symmetry combined in various ways. It will be noted that there is no composite axis of 3-fold (or one-fold) symmetry.  $A_1$  of row 1 is really no symmetry at all while  $A_1 \cdot P$  is simply a plane of symmetry by itself. By combining several axes with periods greater than 2 we have five more classes:  $3A_2 \cdot 4A_3$ ;  $3A_4 \cdot 4A_3 \cdot 3A_2$ ;  $3A_2 \cdot 4A_3 \cdot 3P$ ;  $3A_2 \cdot 4A_3 \cdot 6P$ , and  $6A_2 \cdot 4A_3 \cdot 3A_4 \cdot 9P$ .

These constitute the **thirty-two crystal classes**. Examples of all of these but one ( $A_1 \cdot P$ ) have been found either among minerals, or compounds made in the laboratory. It is interesting to note that just as Mendeléef, the Russian chemist, predicted the existence and even the properties of several chemical elements by the discovery of the periodic law, so Hessel, a German mathematician, in 1830 predicted the thirty-two crystal classes when representatives of only seventeen of them were known.

The table on pages 22-3 gives the name of the class, the number of faces in the general form, the symmetry, and typical examples of minerals and prepared compounds. The name of the form with the symbol  $\{hkl\}$  or  $\{hk\bar{l}\}$ , or the **general form** as it is called, gives the name to the class. In contradistinction, the other forms are called **limit forms**. This term may be explained by considering a pyramidal face ( $hkl$ ). By increasing its intercept on the vertical axes it becomes steeper and steeper, its limit in this case being the prism ( $hk0$ ). By decreasing its intercept on the vertical axis it becomes less steep, its limit in this case being the pinacoid ( $001$ ).

The forms corresponding to the type symbols in any class may be found from the symmetry by a graphical method. Indicate the  $a$ - and  $b$ -axes by two dotted lines at right angles, their intersection being the projection of the  $c$ -axis. Then indicate the symmetry elements in their proper positions by the following



Table of the Thirty-two Crystal Classes

Sys-tem	No.	Name of Class	Faces in General Form	Symmetry	Example of a Mineral	Example of a Prepared Compound
Tri- clinic	1	Pedial (or Asymmetric)	1	No symmetry.	—	$\text{SrH}_2(\text{C}_4\text{H}_9\text{O})_2 \cdot 4\text{H}_2\text{O}$
	2	Pinacoidal	2	$\mathcal{P}_2 = (\text{C})$	Axinite	$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$
Mono- clinic	3	Sphenoidal	2	$\text{A}_2$	Fichtelite	$\text{C}_4\text{H}_6\text{O}_6$
	4	Domatic	2	P	Clinohedrite	$\text{K}_2\text{S}_2\text{O}_8$
	5	Prismatic	4	$\text{A}_2\text{P}$ (C)	Gypsum	$\text{K}_2\text{Mg}(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}$
Ortho- rhombic	6	Rhombic bisphenoidal	4	$3\text{A}_2$	Epsomite	$\text{AgNO}_3$
	7	Rhombic pyramidal	4	$\text{A}_2\text{P}$	Calamine	$\text{C}_6\text{H}_8\text{O}_4$
	8	Rhombic bipyramidal	8	$3\text{A}_2\text{P}$ (C)	Barite	$\text{K}_2\text{SO}_4$
Tetragonal	9	Tetragonal bisphenoidal	4	$\mathcal{P}_4$	—	$\text{Ca}_2\text{Al}_2\text{SiO}_7$
	10	Tetragonal pyramidal	4	$\text{A}_4$	Wulfenite(?)	$\text{Ba}(\text{SbO})_2(\text{C}_4\text{H}_9\text{O})_2 \cdot \text{H}_2\text{O}$
	11	Tetragonal scalenohedral	8	$\mathcal{P}_4\text{A}_2\text{P}$	Chalcopyrite	$\text{Hg}(\text{CN})_2$
	12	Tetragonal trapezohedral	8	$\text{A}_4\text{A}_2$	—	$\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$
	13	Tetragonal bipyramidal	8	$\text{A}_4\text{P}$ (C)	Scheelite	$\text{C}_4\text{H}_8\text{O}_4$
	14	Ditetragonal pyramidal	8	$\text{A}_4\text{P}$	—	$\text{AgF} \cdot \text{H}_2\text{O}$
	15	Ditetragonal bipyramidal	16	$\text{A}_4\text{A}_2\text{P}$ (C)	Zircon	$\text{K}_2\text{Fe}(\text{CN})_6 \cdot 3\text{H}_2\text{O}$

Table of the Thirty-two Crystal Classes—Continued

Sys-tem	No.	Name of Class	Faces in General Form	Symmetry	Example of a Mineral	Example of a Prepared Compound
Hexagonal	16	Trigonal pyramidal	3	$A_3$	—	$\text{Na IO}_3 \cdot 3\text{H}_2\text{O}$
	17	Rhombohedral	6	$P_6$	Phenacite	$\cdot (\text{NH}_4)_2\text{I}_2\text{O}_6 \cdot 3\text{H}_2\text{O}$
	18	Trigonal trapezohedral	6	$A_3 \cdot 3A_2$	Quartz	$\text{PbS}_2\text{O}_6 \cdot 4\text{H}_2\text{O}$
	19	Trigonal bipyramidal	6	$A_3 \cdot P$	—	$\text{NaLiSO}_4$
	20	Trigonal pyramidal	6	$A_3 \cdot 3P$	Tourmaline	$\text{NaNO}_3$
	21	Ditrigonal scalenohedral	12	$P_6 \cdot 3A_2 \cdot 3P$	Calcite	$\text{Ag}_3\text{HPO}_4$
	22	Ditrigonal bipyramidal	12	$A_3 \cdot 3A_2 \cdot 4P$	Benitoite (?)	$\text{KLiSO}_4$
	23	Hexagonal pyramidal	6	$A_6$	Nephelite	$\text{Ba}(\text{SbO})_3(\text{C}_4\text{H}_4\text{O}_6)_2 \cdot \text{KNO}_3$
	24	Hexagonal trapezohedral	12	$A_6 \cdot 6A_2$	—	—
	25	Hexagonal bipyramidal	12	$A_6 \cdot P$	Apatite	$\text{ZnO}$
	26	Dihexagonal pyramidal	12	$A_6 \cdot 6P$	Iodryite	$\text{Mg}$
	27	Dihexagonal bipyramidal	24	$A_6 \cdot 6A_2 \cdot 7P$	Beryl	$\text{Pb}(\text{NO}_3)_2$
Isometric	28	Tetartoidal	12	$3A_2 \cdot 4A_3$	Ullmannite	$\text{NH}_4\text{Cl}$
	29	Gyroïdal	24	$6A_2 \cdot 4A_3 \cdot 3A_4$	Cuprite (?)	$\text{KAl}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$
	30	Diploïdal	24	$3A_2 \cdot 4A_3 \cdot 3P$	Pyrite	$\text{KNa}_2\text{Al}(\text{C}_2\text{O}_4)_2 \cdot 4\text{H}_2\text{O}$
	31	Hextetrahedral	24	$3A_2 \cdot 4A_3 \cdot 6P$	Tetrahedrite	$\text{NaCl}$
	32	Hexoctahedral	48	$6A_2 \cdot 4A_3 \cdot 3A_4 \cdot 9P$	Galena	

conventions. A full line represents a plane of symmetry. If the plane of the paper is a plane of symmetry draw a heavy circle of convenient diameter. Denote axes of 2-, 3-, 4-, and 6-fold symmetry by small ellipses, triangles, squares, and hexagons. As an example let it be required to find the forms represented by the type symbols of the rhombic pyramidal class with the symmetry,  $A_2 \cdot 2P$ . In Fig. 53 the two planes of symmetry are represented by two full lines which coincide with the projection of

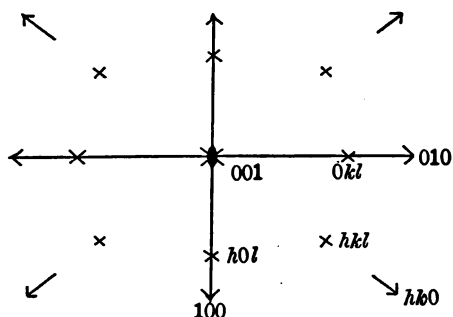


FIG. 53.—Graphical method of determining the names of forms.

the axes,  $a$  and  $b$ . Their intersection is the axis of two-fold symmetry. Projections of the faces in the upper octants are small crosses. Faces parallel to the vertical axis may be indicated by arrows. The general form of this class is a rhombic pyramid, for the symmetry requires  $(\bar{h}kl)$ ,  $(h\bar{k}l)$ , and  $(h\bar{h}l)$  to

accompany  $(hkl)$ . For a face  $(0kl)$ , the symmetry requires  $(0\bar{k}l)$ ; the form, then, is a dome. Similarly  $\{h0l\}$  is a dome;  $\{hk0\}$  is a rhombic prism;  $\{100\}$  and  $\{010\}$  are each pinacoids, while  $\{001\}$  is a pedion consisting of a single face. In the lower half of the crystal  $\{hk\bar{l}\}$  is a rhombic pyramid;  $\{0k\bar{l}\}$  and  $\{h0\bar{l}\}$ , domes; while  $\{00\bar{1}\}$  is a pedion. The forms on the lower half of the crystal in this case are independent of those on the upper half.

Certain classes have properties in common and may be assembled in larger groups called **systems**. The first two classes have no directions fixed by symmetry, class 1 having no symmetry at all, while in class 2 any direction is an axis of 2-fold composite symmetry. These two classes constitute the **trigonal system**. Classes 3, 4, and 5 each have one direction fixed by symmetry, either an  $A_2$  or a line normal to  $P$ . These three

classes constitute the **monoclinic system**. Classes 6, 7, and 8 have three directions at right angles which are fixed by symmetry. They constitute the **orthorhombic system**. Classes 9 to 15 have one direction of 4-fold symmetry (including two classes with composite symmetry) and constitute the **tetragonal system**. Classes 16 to 27 have one direction of either 3-fold or 6-fold symmetry and constitute the **hexagonal system**. The **isometric system** consists of five classes each with four directions of 3-fold symmetry. Except for the isometric system these fixed directions are axes of reference.

The axes of reference for the various systems are as follows:

**Triclinic.** Three non-interchangeable axes at oblique angles. Fig. 108, page 38.

**Monoclinic.** Three non-interchangeable axes, two at oblique angles, the third at right angles to the plane of these two. Fig. 82, page 32.

**Orthorhombic.** Three non-interchangeable axes at right angles. Fig. 62, page 27.

**Tetragonal.** Three axes at right angles, two of which are interchangeable. Fig. 111, page 39.

**Isometric.** Three interchangeable axes at right angles. Fig. 175, page 55.

**Hexagonal.** Four axes, one at right angles to three interchangeable ones which are in one plane and intersect each other at angles of  $120^\circ$ . Fig. 132, page 44.

The forms of the crystal class with the highest grade of symmetry in each system are sometimes called **holohedral** or whole forms, while many of the forms of the classes of lower grade of symmetry are called **hemihedral** or half forms, because they have half the number of faces of the holohedral forms. There is a geometrical resemblance between these two kinds of forms. A tetrahedron is the hemihedral form of an octahedron, for it may be

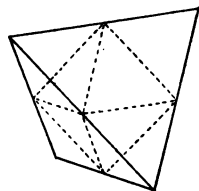
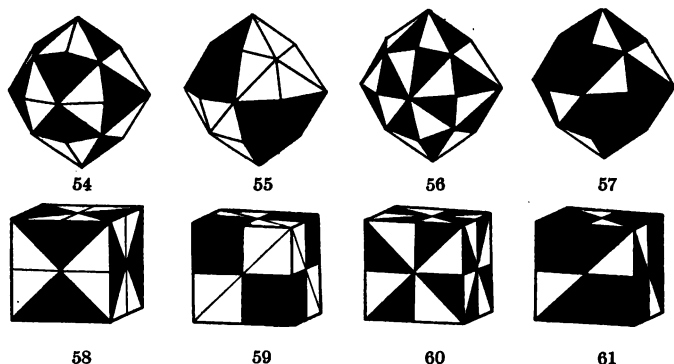


FIG. 53a.—Tetrahedron derived from the octahedron.

derived by extending alternate faces and suppressing the others as in Fig. 53a. A cube has no hemihedral form, or rather the hemihedral and holohedral cubes are geometrically identical, for the suppression of alternate octants still leaves the cube (see Figs. 58–61).

The symmetrical suppression of the faces of the general forms of the six holohedral classes gives rise to twenty-six divisions. These together with the six holohedral divisions lead to the thirty-two classes before mentioned. The general forms of the five isometric classes may be derived from the hexoctahedron



FIGS. 54–61.—To illustrate hemihedrism.

thus: The suppression of faces of alternate octants (Fig. 56) gives the hextetrahedron, the suppression of alternate faces (Fig. 56) gives the gyroid, the suppression of faces in pairs astride the planes of symmetry (Fig. 54) gives the diploid, while the combination of any two of these methods (Fig. 57) gives a twelve-sided figure called the tetartoid. As this form has one-fourth the number of faces of the hexoctahedron it is called a **tetartohedral** or quarter form. Figs. 58 to 61 show that the cube is common to all five isometric classes.

As hemihedrism is due to the *symmetrical* suppression of faces it is mainly a question of terms. In most of the modern works on crystallography hemihedrism is not considered, for there is no

structural connection between the holohedral and hemihedral forms. The holohedral classes are sometimes called normal groups, but they are really no more normal than the classes with lower symmetry.

## 6. THE ORTHORHOMBIC SYSTEM

The orthorhombic system includes all crystals that can be referred to three non-interchangeable axes of reference at right angles to each other. The axial elements are  $a:b:c$ . Conventionally  $b$  is unity and  $a$  is always less than unity. These values

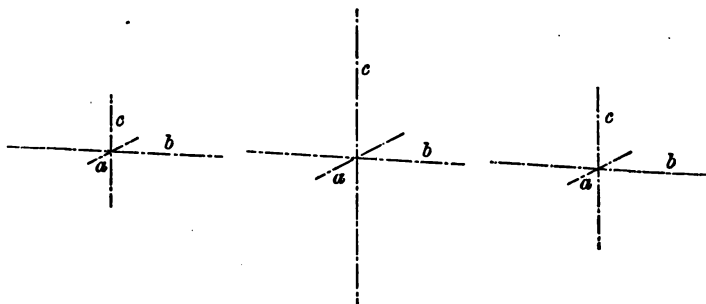


FIG. 62.  
Axes for topaz.

FIG. 63.  
Axes for barite.

FIG. 64.  
Axes for cerussite.

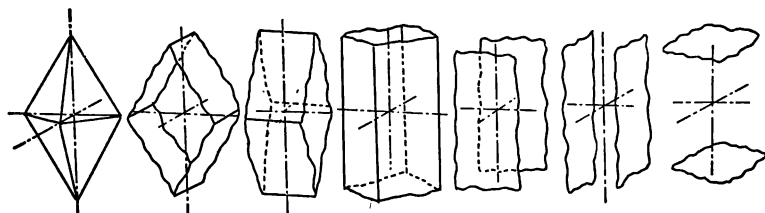
differ for every orthorhombic substance. Figs. 62, 63, and 64 represent the unit lengths of the axes for topaz, barite, and cerussite respectively.

### Rhombic Bipyramidal Class. $3A_2 \cdot 3P(C)$

(*Holohedral*)

The three axes of 2-fold symmetry are the axes of reference. The selection of the  $c$ -axis is arbitrary, but of the other two  $a$  is always shorter than  $b$ .

<b>Rhombic bipyramid</b>	8 faces	$\{hkl\}$	(Rhombic pyramid) <sup>1</sup>
<b>Rhombic prism</b>	4 faces	$\{0kl\}$	(Brachydome)
<b>Rhombic prism</b>	4 faces	$\{h0l\}$	(Macrodome)
<b>Rhombic prism</b>	4 faces	$\{hk0\}$	(Rhombic prism)
<b>Pinacoid</b>	2 faces	$\{100\}$	(Macropinacoid)
<b>Pinacoid</b>	2 faces	$\{010\}$	(Brachypinacoid)
<b>Pinacoid</b>	2 faces	$\{001\}$	(Basal pinacoid)



65  $\{hkl\}$     66  $\{0kl\}$     67  $\{h0l\}$     68  $\{hk0\}$     69  $\{100\}$     70  $\{010\}$     71  $\{001\}$ .

Figs. 65-71.—The seven orthorhombic type forms.

**Rhombic Pyramid  $\{hkl\}$**  (Rhombic pyramid). The general form of this class consists of eight faces. In the ideal form the faces are scalene triangles (Fig. 65). For any one substance there is a great variety of forms possible depending upon various rational values of  $h$ ,  $k$ , and  $l$ . If  $h$  and  $k$  are equal we have  $\{hhl\}$  of which there is a series with varying values of  $l$ . As these forms are in a vertical zone with the unit prism  $\{110\}$ , they are called bipyramids of the unit-series.  $\{111\}$  is the unit bipyramid.

**Rhombic Prism  $\{0kl\}$**  (Brachydome). A horizontal open form composed of four faces each parallel to the  $a$ -axis (Fig. 66). There is a series of all possible rational values of  $k$  and  $l$ .

**Rhombic Prism  $\{h0l\}$**  (Macrodome). A horizontal open form composed of four faces each parallel to the  $b$ -axis (Fig. 67). There is also a series varying from  $\{001\}$  to  $\{010\}$  for all possible values of  $h$  and  $l$ .

**Rhombic Prism  $\{hk0\}$**  (Rhombic prism). An open form consisting of four vertical faces (Fig. 68). For each orthorhombic

<sup>1</sup> These names are used by some authors.

bic mineral a whole series of prisms is possible ranging from  $\{010\}$  to  $\{100\}$ . The unit prism is  $\{110\}$ .

**Pinacoid  $\{100\}$**  (Macropinacoid). This form may be called the *front pinacoid* as it consists of two opposite parallel faces, one in front and one behind (Fig. 69). As there is only one pinacoid of this kind possible, the symbol  $\{100\}$  is used instead of  $\{h00\}$ .

**Pinacoid  $\{010\}$**  (Brachypinacoid). This form, consisting of two parallel faces, one on the right and one on the left, may be called the *side pinacoid* (Fig. 70). The symbol is written  $\{010\}$  instead of  $\{0k0\}$ .

**Pinacoid  $\{001\}$**  (Basal pinacoid). This form may be called the *top pinacoid* (Fig. 71). The symbol is written  $\{001\}$  instead of  $\{00l\}$ .

**Combinations.** Only the bipyramids can occur alone. All other crystals are combinations of two or more forms. There are manifold combinations and consequently a great variety in the habit. The most common are tabular, prismatic, and pyramidal, but some crystals cannot be placed under either of these. Pseudo-hexagonal orthorhombic crystals are common, but careful measurement distinguishes them from hexagonal crystals.

### Examples

Examples of orthorhombic crystals are numerous among both minerals and prepared compounds. Barite,  $\text{BaSO}_4$ , and topaz,  $\text{Al}_2\text{F}_2\text{SiO}_4$ , are given as typical examples for study and practice in working out the forms.

**Barite.**  $a:b:c=0.815:1:1.313$ . Usual forms:  $c\{001\}$ ,  $m\{110\}$ ,  $o\{011\}$ ,  $d\{102\}$ ,  $l\{104\}$ . Cleavage parallel to  $c$  and  $m$ . Interfacial angles:  $mm(110:1\bar{1}0)=78^\circ 22\frac{1}{2}'$ ;  $cm(001:110)=90^\circ$ ;  $co(001:011)=52^\circ 43'$ ;  $cd(001:102)=38^\circ 51'$ ;  $cl(001:104)=21^\circ 56'$ .

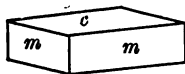


FIG. 72.

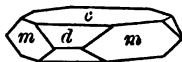


FIG. 73.



FIG. 74.

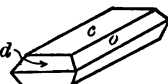


FIG. 75.



Figs. 72 to 75 are usual combinations. Fig. 50, page 17, is more complex with  $a\{100\}$ ,  $u\{101\}$ ,  $z\{111\}$ , and  $y\{122\}$  in addition to the above.

**Topaz.**  $a:b:c=0.528:1:0.477$ . Usual forms:  $m\{110\}$ ,  $l\{120\}$ ,  $c\{001\}$ ,  $f\{021\}$ ,  $y\{041\}$ ,  $u\{111\}$ ,  $o\{221\}$ ,  $i\{223\}$ . Cleavage parallel to  $c$ . Interfacial angles:  $mm\{110:1\bar{1}0\}=55^\circ 43'$ ;  $ll\{120:\bar{1}20\}=86^\circ 49'$ ;  $cf\{001:021\}=43^\circ 39'$ ;  $cy\{001:041\}=62^\circ 21'$ ;  $ci\{001:223\}=34^\circ 14'$ ;  $cu\{001:111\}=45^\circ 35'$ ;  $co\{001:221\}=$

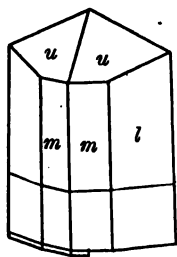


FIG. 76.

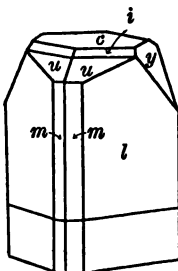


FIG. 77.

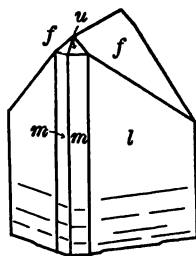


FIG. 78.

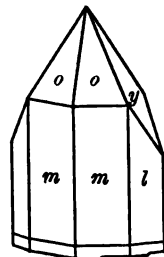


FIG. 79.

FIGS. 76-79.—Topaz crystals.

$63^\circ 54'$ ;  $uu\{111:1\bar{1}1\}=39^\circ 0'$ ;  $oo\{221:2\bar{2}1\}=49^\circ 38'$ . Figs. 76 to 79 represent usual types of topaz crystals. The lower part of these figures represents cleavage, as doubly terminated crystals are very rare.

### RHOMBIC PYRAMIDAL CLASS. $A_2 \cdot 2P$

(Hemimorphic)

$A_2$  is taken as the  $c$ -axis, the other two axes being perpendicular to  $c$ , one in each plane of symmetry. The type forms are as follows:

Rhombic pyramids	$\{hkl\}$ , $\{hkl\bar{l}\}$
Domes	$\{0kl\}$ , $\{0k\bar{l}\}$ ; $\{h0l\}$ , $\{h0\bar{l}\}$
Rhombic prism	$\{hko\}$
Pinacoids	$\{100\}$ , $\{010\}$
Pedions	$\{001\}$ , $\{00\bar{1}\}$

Calamine,  $\text{Zn}_2(\text{OH})_2\text{SiO}_3$ , is the only common mineral belonging to this class. Fig. 80 represents a typical crystal with the pedion  $c\{001\}$ , the domes  $t\{301\}$  and  $i\{031\}$ , the pinacoid  $b\{010\}$ , the rhombic prism  $m\{110\}$ , and the rhombic pyramid  $v\{12\bar{1}\}$ . The two ends of the class are different hence the term, *hemimorphic*, sometimes used.

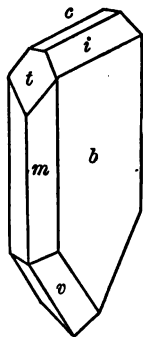


FIG. 80.—Calamine.

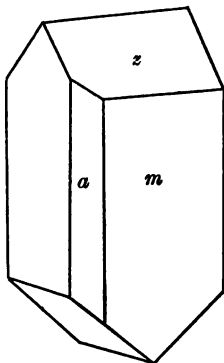


FIG. 81.—Epsomite.

### RHOMBIC BISPHENOIDAL CLASS. $3A_2$

#### (Hemihedral)

The three axes of symmetry are the axes of reference. The type forms are as follows:

Rhombic bisphenoids

Rhombic prisms

Pinacoids

$\{hkl\}$ ,  $\{h\bar{k}l\}$

$\{0kl\}$ ,  $\{h0l\}$ ,  $\{hk0\}$

$\{100\}$ ,  $\{010\}$ ,  $\{001\}$

Epsomite ( $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ ) is the best known example of this class. Fig. 81 is a typical crystal with the forms  $m\{110\}$ ,  $z\{111\}$ , and  $a\{100\}$ .

## 7. THE MONOCLINIC SYSTEM

The monoclinic system includes all crystals that can be referred to three non-interchangeable axes of reference, one at

right angles to the other two, which are inclined to each other. The axial elements are  $a:b:c$  and  $\beta$ , the acute angle between the  $a$ - and  $c$ -axes (see Fig. 82). The  $a$ -axis may be either shorter or longer than the  $b$ -axis which is taken as unity. The crystal is held so that the  $a$ -axis points down and toward the observer.

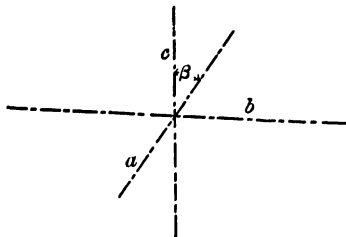


FIG. 82.—Monoclinic axes.

### Prismatic Class. $A_2 \cdot P \cdot (C)$

(*Holohedral*)

The axis of 2-fold symmetry is the  $b$ -axis. The axes  $a$  and  $c$  are in the plane of symmetry, but their position is more or less arbitrary. They are usually taken parallel to prominent edges or faces.

Rhombic prisms	4 faces	$\{hkl\}$ , $\{\bar{h}kl\}$	(Hemi-pyramids)
Rhombic prism	4 faces	$\{0kl\}$	(Clinodome)
Rhombic prism	4 faces	$\{hk0\}$	(Prism)
Pinacoids	2 faces	$\{h0l\}$ , $\{\bar{h}0l\}$	(Hemi-orthodomes)
Pinacoid	2 faces	$\{00l\}$	(Orthopinacoid)
Pinacoid	2 faces	$\{0l0\}$	(Clinopinacoid)
Pinacoid	2 faces	$\{001\}$	(Basal pinacoid)

**Rhombic Prisms**  $\{hkl\}$ ,  $\{\bar{h}kl\}$  (Hemi-pyramids). These two forms occur independently but together they constitute a figure that resembles a pyramid, hence the name hemi-pyramid sometimes used. Fig. 83 represents an  $\{hkl\}$  form.

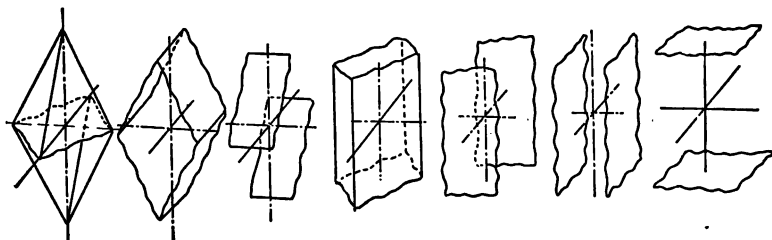
**Rhombic Prism**  $\{0kl\}$  (Clinodome). An open form consisting

of four faces each parallel to the  $a$ -axis. The  $a$ -axis is sometimes called the clino-axis hence the name clino-dome. Fig. 84.

**Rhombic Prism**  $\{hk0\}$  (Prism). An open form consisting of four faces each parallel to the vertical axis (Fig. 86).

**Pinacoids**  $\{h0l\}$ ,  $\{\bar{h}0l\}$ . (Hemi-orthodomes). These forms, each composed of two opposite parallel faces parallel to the  $b$ -axis (often called the ortho-axis), are independent. Fig. 85 represents  $\{h0l\}$ .

**Pinacoid**  $\{100\}$  (Orthopinacoid). This form may be called the *front pinacoid*, but is also known as the orthopinacoid. Fig. 87.



83  $\{hkl\}$ . 84  $\{0kl\}$ . 85  $\{h0l\}$ . 86  $\{hk0\}$ . 87  $\{100\}$ . 88  $\{010\}$ . 89  $\{001\}$ .

Figs. 83-89.—The seven monoclinic type forms.

**Pinacoid**  $\{010\}$  (Clinopinacoid). This may be called the *side-pinacoid*, but is also known as the clinopinacoid. Fig. 88.

**Pinacoid**  $\{001\}$  (Basal pinacoid). This form is usually known as the basal pinacoid, but its faces are inclined and not perpendicular to the  $c$ -axis. Fig. 89.

**Combinations.** All monoclinic crystals are necessarily combinations of two or more forms, as all the forms are open ones. As in the orthorhombic system the habits are quite diversified. If the angle  $\beta$  is close to  $90^\circ$  there is often close resemblance to orthorhombic crystals, but this result may also be due to equal development of front and back faces. Prismatic crystals are usually elongated in the direction of the  $c$ -axis, but occasionally in the direction of the  $b$ -axis, as in the case of epidote, and in the direction of the  $a$ -axis, as in orthoclase.

## Examples

Many minerals and also artificially prepared compounds crystallize in this class. Orthoclase ( $\text{KAlSi}_3\text{O}_8$ ), diopside ( $\text{CaMgSi}_2\text{O}_6$ ), augite ( $\text{R}^{\text{II}}\text{SiO}_3$ ), and gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) are given as good examples for study and practice.

**Orthoclase.**  $a:b:c=0.658:1:0.555$ ;  $\beta=63^\circ 57'$ . Usual forms:  $c\{001\}$ ,  $b\{010\}$ ,  $m\{110\}$ ,  $z\{130\}$ ,  $x\{\bar{1}01\}$ ,  $y\{\bar{2}01\}$ ,  $n\{021\}$ ,  $o\{\bar{1}11\}$ . Cleavage parallel to  $c$  and  $b$ . Interfacial angles:

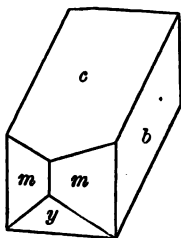


FIG. 90.

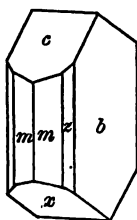


FIG. 91.

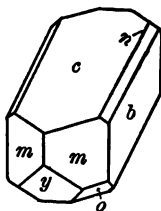


FIG. 92.

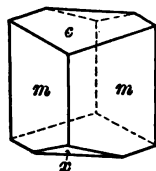


FIG. 93.

FIGS. 90-93.—Orthoclase crystals.

$mm(110:\bar{1}\bar{1}0)=61^\circ 13'$ ;  $bz(010:130)=29^\circ 24'$ ;  $cx(001:\bar{1}01)=50^\circ 16'$ ;  $cy(001:\bar{2}01)=80^\circ 18'$ ;  $cn(001:021)=44^\circ 56'$ ;  $bo(010:\bar{1}11)=63^\circ 8'$ ;  $bc(010:001)=90^\circ 0'$ ;  $cm(001:110)=67^\circ 47'$ . Figs. 90-93 represent usual types of crystals.

**Diopside.**  $a:b:c=1.092:1:0.589$ ;  $\beta=74^\circ 10'$ . Usual forms:  $c\{001\}$ ,  $b\{010\}$ ,  $a\{100\}$ ,  $m\{110\}$ ,  $p\{111\}$ ,  $o\{\bar{2}21\}$ ,  $d\{\bar{1}01\}$ ,  $\bar{4}\{\bar{3}11\}$ ,  $s\{\bar{1}11\}$ . Interfacial angles:  $mm(110:1\bar{1}0)=92^\circ 50'$ ;  $ab(100:010)=90^\circ 0'$ ;  $ac(001:001)=74^\circ 10'$ ;  $bc(010:001)=90^\circ 0'$ ;  $pp(111:\bar{1}\bar{1}1)=48^\circ 29'$ ;  $cp(001:111)=33^\circ 50'$ ;  $ss(\bar{1}11:\bar{1}\bar{1}1)=59^\circ 11'$ ;  $oo(\bar{2}21:\bar{2}21)=84^\circ 11'$ ;  $\bar{4}\bar{4}(\bar{3}11:\bar{3}11)=37^\circ 50'$ ;  $cd(001:\bar{1}01)=31^\circ 20'$ . Figs. 94-97 represent typical crystals of diopside. The striations on Fig. 94 are due to polysynthetic twinning with  $\{001\}$  as twin-plane.

**Augite.** Axial elements, usual forms, and interfacial angles practically as in diopside. Figs. 98 to 101 represent the common

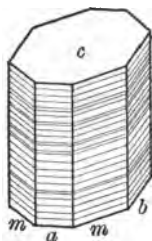


FIG. 94.

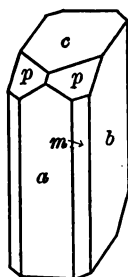


FIG. 95.

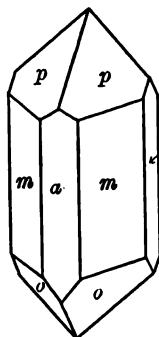


FIG. 96.

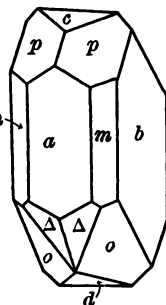


FIG. 97.

FIGS. 94-97.—Diopside crystals.

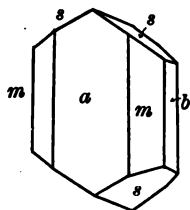


FIG. 98.

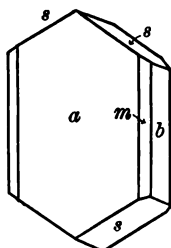


FIG. 99.

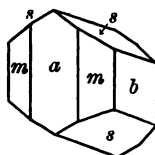


FIG. 100.

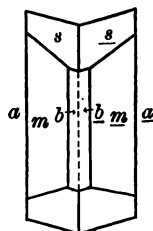


FIG. 101.

FIGS. 98-101.—Augite crystals.

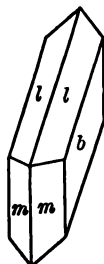


FIG. 102.

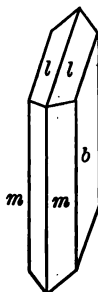


FIG. 103.

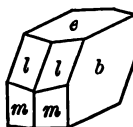


FIG. 104.

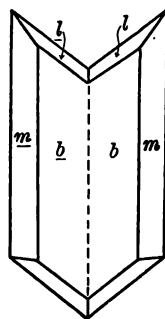


FIG. 105.

FIGS. 102-105.—Gypsum crystals.

types of augite crystals. Twins with  $\{100\}$  as twin-plane are common as shown in Fig. 101.

**Gypsum.**  $a:b:c=0.690:1:0.412$ ;  $\beta=80^\circ 42'$ . Usual forms:  $m\{110\}$ ,  $l\{111\}$ ,  $b\{010\}$ ,  $e\{\bar{1}03\}$ . Cleavage parallel to  $b$ . Interfacial angles:  $mm(110:\bar{1}\bar{1}0)=68^\circ 30'$ ;  $ll(111:\bar{1}\bar{1}\bar{1})=36^\circ 12'$ ;  $be(010:\bar{1}03)=90^\circ 0'$ ;  $ae(\text{edge } \bar{1}\bar{1}0, \bar{1}\bar{1}0:\bar{1}03)=87^\circ 49'$ . The usual combination is  $bml$ , but with varying habit as represented in Figs. 102 and 103. Fig. 105 represents a twin crystal with  $\{100\}$  as twin-plane.

### DOMATIC CLASS. P.

#### (Hemihedral)

The  $b$ -axis is normal to the plane of symmetry, the  $a$  and  $c$  axes being in the plane of symmetry.

Domes

$\{hkl\}$ ,  $\{\bar{h}kl\}$ ,  $\{h\bar{k}l\}$ ,  $\{\bar{h}\bar{k}l\}$

Domes

$\{0kl\}$ ,  $\{0\bar{k}l\}$

Pinacoid

$\{010\}$

Pedions

$\{100\}$ ,  $\{\bar{1}00\}$ ;  $\{001\}$ ,  $\{00\bar{1}\}$ ;  $\{h0l\}$ ,  $\{\bar{h}0l\}$ .

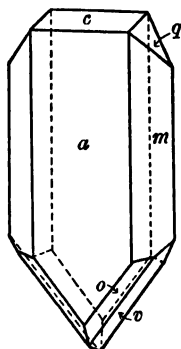


Fig. 106.— $K_2S_4O_6$ .

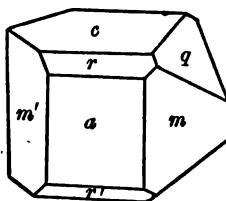


Fig. 107.—Tartaric acid.

Clinohedrite,  $CaZn(OH)_2SiO_3$ , is the only mineral known to belong to this class. There are several representatives among artificially prepared compounds, among them potassium tetrathionate,  $K_2S_4O_6$ , a crystal of which is represented by Fig. 106.

SPHENOIDAL CLASS.  $A_2$ 

(Hemimorphic)

The axis of 2-fold symmetry is the  $b$ -axis, the  $a$  and  $c$  axes being in a plane normal to this axis.

Sphenoids  $\{hkl\}$ ,  $\{\bar{h}kl\}$ ,  $\{\bar{h}\bar{k}l\}$ ,  $\{h\bar{k}l\}$ ;  $\{0kl\}$ ,  $\{0\bar{k}l\}$ ;  $\{hk0\}$ ,  $\{h\bar{k}0\}$

Pinacoids  $\{h0l\}$ ,  $\{\bar{h}0l\}$ ;  $\{100\}$ ,  $\{001\}$

Pedions  $\{010\}$ ,  $\{0\bar{1}0\}$

Fichtelite,  $C_{18}H_{32}$ , belongs to this class. Fig. 107 represents a crystal of tartaric acid, which also belongs here. Cane sugar is another example.

## 8. THE TRICLINIC SYSTEM

The triclinic system includes all crystals that can be referred to three non-interchangeable axes at oblique angles. The axial elements are  $a:b:c$ , ( $b$  being unity, and  $a$  always less than unity) and the angles  $\alpha$ ,  $\beta$ , and  $\gamma$  between the axes  $b$  and  $c$ ,  $a$  and  $c$ ,  $a$  and  $b$  respectively. Fig. 108 represents a triclinic axial cross.

Pinacoidal Class.  $P_2(C)$ 

(Holohedral)

The choice of axes is arbitrary, but they are usually taken parallel to the intersection edges of the three most prominent faces.

Pinacoids	2 faces	$\{hkl\}$ , $\{\bar{h}kl\}$ , $\{h\bar{k}l\}$ , $\{\bar{h}\bar{k}l\}$	(Tetarto-pyramids)
Pinacoids	2 faces	$\{h0l\}$ , $\{\bar{h}0l\}$	(Hemi-macrodomes)
Pinacoids	2 faces	$\{0kl\}$ , $\{0\bar{k}l\}$	(Hemi-brachydomes)
Pinacoids	2 faces	$\{hk0\}$ , $\{h\bar{k}0\}$	(Hemi-prisms)
Pinacoid	2 faces	$\{100\}$	(Macropinacoid)
Pinacoid	2 faces	$\{010\}$	(Brachypinacoid)
Pinacoid	2 faces	$\{001\}$	(Basal pinacoid)

All forms are pinacoids consisting of two opposite parallel faces.



**Combinations.** The appearance of triclinic crystals depends largely upon the obliquity of the axes. Many of them closely approach monoclinic crystals in angles. (See Fig. 534, page 389.) This is especially the case with the plagioclase feldspars. In albite, for example,  $\alpha=94^\circ$  and  $\gamma=88^\circ$ .

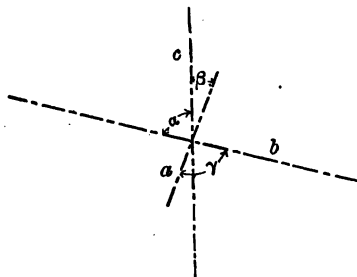


FIG. 108.—Triclinic axes.

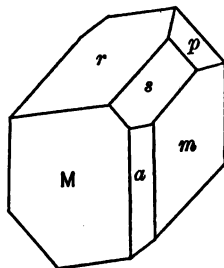


FIG. 109.—Axinite.

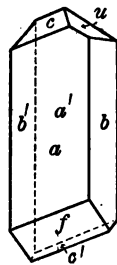


FIG. 110.

### Examples

Comparatively few minerals crystallize in this class. Axinite, though without much variation in habit, is the most available triclinic mineral for study.

**Axinite.**  $a:b:c=0.492:1:0.479$ ;  $\alpha=82^\circ 54'$ ,  $\beta=91^\circ 52'$ ,  $\gamma=131^\circ 32'$ . Usual forms:  $a\{100\}$ ,  $m\{110\}$ ,  $M\{1\bar{1}0\}$ ,  $s\{201\}$ ,  $p\{111\}$ ,  $r\{1\bar{1}1\}$ . Interfacial angles:  $mM(110:\bar{1}10)=44^\circ 29'$ ;  $ms(110:201)=27^\circ 57'$ ;  $sr(201:\bar{1}11)=36^\circ 25'$ ;  $Mr(1\bar{1}0:\bar{1}11)=45^\circ 15'$ ;  $sp(201:111)=16^\circ 7'$ . Fig. 109 is a drawing of a typical crystal of axinite.

PEDIA ~~CL~~ CLASS. (No symmetry)

(Hemihedral)

Although there are no symmetry elements whatever, this constitutes a crystal class, for crystals without symmetry may have faces with rational indices. The rationality of indices is entirely independent of symmetry.

In this class all forms are pedions consisting of one face only. Two parallel faces, even if they have about the same size and shape, are separate forms. There are twenty-six separate kinds of forms possible, using the sign permutations with the seven type symbols.

No mineral representative of this class has yet been discovered, but several artificially prepared compounds belong here. Fig. 110 represents a crystal of hydrous acid strontium tartrate with the forms:  $c\{001\}$ ,  $c'\{00\bar{1}\}$ ,  $b\{010\}$ ,  $b'\{0\bar{1}0\}$ ,  $a\{100\}$ ,  $a'\{\bar{1}00\}$ ,  $u\{\bar{1}22\}$ , and  $f\{10\bar{1}\}$ .

## 9. THE TETRAGONAL SYSTEM

The tetragonal system includes all crystals that can be referred to three axes at right angles, two of which are interchangeable. The axes are designated  $a_1:a_2:c$ ,  $a_1$  and  $a_2$  each equal to unity and  $c$  either greater or less than unity. Fig. 111 represents the axes for zircon.

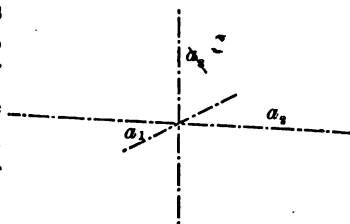


FIG. 111.—Tetragonal axes.

### Ditetragonal Bipyramidal Class. $A_4 \cdot 4A_2 \cdot 5P \cdot (C)$

(*Holohedral*)

The axis of 4-fold symmetry is the  $c$ -axis. As there are four axes of 2-fold symmetry at  $45^\circ$  to each other, either pair at right angles to each other may be selected as the lateral axes.

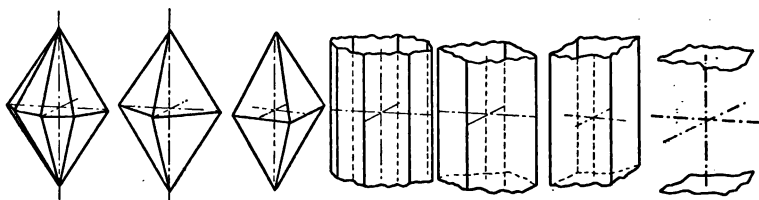
Ditetragonal bipyramid	16 faces	$\{hkl\}$	(Ditetragonal pyramid)
Tetragonal bipyramid	8 faces	$\{hhl\}$	(Pyramid of first order)
Tetragonal bipyramid	8 faces	$\{h0l\}$	(Pyramid of second order)
Ditetragonal prism	8 faces	$\{hk0\}$	(Ditetragonal prism)
Tetragonal prism	4 faces	$\{110\}$	(Prism of first order)
Tetragonal prism	4 faces	$\{100\}$	(Prism of second order)
Pinacoid	2 faces	$\{001\}$	(Basal pinacoid)

**Ditetragonal Bipyramid  $\{hkl\}$**  (Ditetragonal pyramid). The general form consists of sixteen faces, the faces in the ideal form being scalene triangles (Fig. 112). The angles over alternate polar edges are equal.

**Tetragonal Bipyramid  $\{hhl\}$**  (Pyramid of the first order). This form cuts the lateral axes at equal distances (Fig. 113).

**Tetragonal Bipyramid  $\{h0l\}$**  (Pyramid of the second order). A form consisting of eight faces each parallel to one lateral axis (Fig. 114). This form and  $\{hhl\}$  are identical except in position.

**Ditetragonal Prism  $\{hko\}$**  (Ditetragonal prism). An open form consisting of eight faces, each parallel to the vertical axis (Fig. 115). The faces meet in angles which are alternately equal.



112 $\{hkl\}$ . 113 $\{hhl\}$  114 $\{h0l\}$ . 115 $\{hko\}$ . 116 $\{110\}$ . 117 $\{100\}$ . 118 $\{001\}$ .

Figs. 112-118.—The seven tetragonal forms.

**Tetragonal Prism  $\{110\}$**  (Prism of the first order). This is an open form with four faces each parallel to the vertical axis (Fig. 116).

**Tetragonal Prism  $\{100\}$**  (Prism of the second order). This is an open form similar to  $\{110\}$  except in position (Fig. 117).

**Pinacoid  $\{001\}$**  (Basal pinacoid). This form possesses two parallel faces, an upper one and a lower one. (Fig. 118).

**Combinations.** The bipyramids are closed forms, but the prisms and pinacoids are open forms, and hence must occur in combination. In habit tetragonal crystals are usually prismatic, pyramidal, or tabular. Pseudo-octahedral and pseudo-cubic crystals are not uncommon.

## Examples

**Zircon.**  $c=0.640$ . Usual forms:  $m\{110\}$ ,  $a\{100\}$ ,  $p\{111\}$ ,  $u\{331\}$ ,  $x\{311\}$ . Interfacial angles:  $mp(110:111)=47^\circ 50'$ ;  $mm(110:\bar{1}\bar{1}0)=90^\circ 0'$ ;  $ma(110:100)=45^\circ 0'$ ;  $mp(110:111)=$

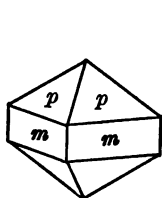


FIG. 119.

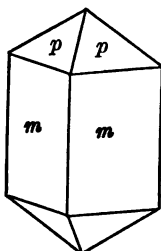


FIG. 120.

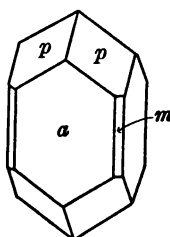


FIG. 121.

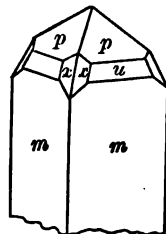


FIG. 122.

FIGS. 119-122.—Zircon.

$47^\circ 50'$ ;  $ap(100:111)=61^\circ 40'$ ;  $mu(110:331)=20^\circ 12'$ ;  $xx(311:3\bar{1}\bar{1})=32^\circ 57'$ ;  $pp(111:\bar{1}\bar{1}1)=56^\circ 40'$ . Figs. 119 to 122 represent the usual combinations and habits.

**Apophyllite.**  $c=1.251$ . Usual forms:  $a\{100\}$ ,  $c\{001\}$ ,  $p\{111\}$ ,  $y\{310\}$ . Cleavage parallel to  $c$ . Interfacial angles:  $cp(001:111)=60^\circ 32'$ ;  $ap(100:111)=52^\circ 0'$ ;  $pp(111:\bar{1}\bar{1}1)=76^\circ 0'$ ;  $ay(100:310)=18^\circ 26'$ .

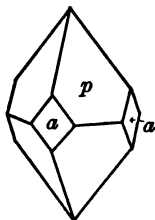


FIG. 123.

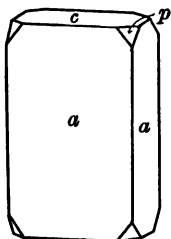


FIG. 124.

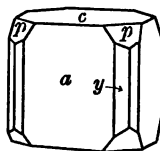


FIG. 125.



FIG. 126.

FIGS. 123-126.—Apophyllite

DITETRAGONAL PYRAMIDAL CLASS.  $A_4 \cdot 4P$ *(Hemimorphic hemihedral)*

Ditetragonal pyramids	$\{hkl\}$ , $\{h\bar{k}l\}$
Tetragonal pyramids	$\{hhl\}$ , $\{h\bar{h}l\}$
Tetragonal pyramids	$\{hol\}$ , $\{h\bar{o}l\}$
Ditetragonal prism	$\{hk0\}$
Tetragonal prism	$\{110\}$
Tetragonal prism	$\{100\}$
Pedions	$\{001\}$ , $\{00\bar{1}\}$

No known minerals belong here. Hydrrous silver fluorid,  $AgF \cdot H_2O$  (Fig. 127), is a representative of this class.

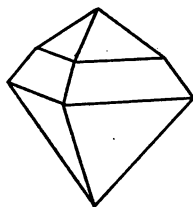


Fig. 127.

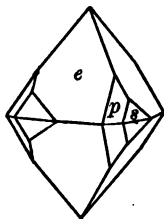


Fig. 128.

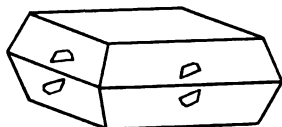


Fig. 129.

TETRAGONAL BIPYRAMIDAL CLASS.  $A_4 \cdot P \cdot (C)$ *(Pyramidal hemihedral)*

Tetragonal bipyramids	$\{hkl\}$ , $\{khl\}$ , $\{h\bar{h}l\}$ , $\{hol\}$
Tetragonal prisms	$\{hk0\}$ , $\{k\bar{h}0\}$ , $\{110\}$ , $\{100\}$
Pinacoid	$\{001\}$

Scheelite,  $CaWO_4$ , is the best example of this class. (Fig. 128).

TETRAGONAL TRAPEZOHEDRAL CLASS.  $A_4 \cdot 4A_2$ *(Trapezohedral hemihedral)*

Tetragonal trapezohedrons	$\{hkl\}$ , $\{khl\}$
Tetragonal bipyramids	$\{hhl\}$ , $\{h\bar{h}l\}$
Ditetragonal prism	$\{hk0\}$
Tetragonal prisms	$\{100\}$ , $\{110\}$
Pinacoid	$\{001\}$

No known minerals belong here. But by means of etch-figures it has been shown that the artificial salt,  $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$ , has the symmetry of this class. Fig. 129 shows the etch-figures on  $\{111\}$ .

TETRAGONAL SCALENOHEDRAL CLASS.  $P_4 \cdot 2A_2 \cdot 2P$   
(*Sphenoidal hemihedral*)

Tetragonal scalenohedrons	$\{hkl\}, \{h\bar{k}l\}$
Tetragonal bisphenoids	$\{hhl\}, \{h\bar{h}l\}$
Tetragonal bipyramid	$\{h0l\}$
Ditetragonal prism	$\{hk0\}$
Tetragonal prisms	$\{110\}, \{100\}$
Pinacoid	$\{001\}$

Chalcopyrite,  $\text{CuFeS}_2$ , is the best known representative of this class. Fig. 130 represents a combination of the tetragonal bisphenoid  $\phi\{772\}$  and the tetragonal scalenohedron  $\chi\{122\}$ .

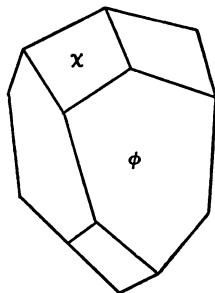


FIG. 130.

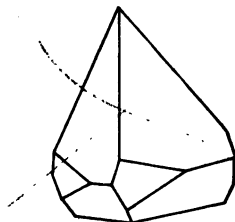


FIG. 131.

TETRAGONAL PYRAMIDAL CLASS.  $A_4$   
(*Hemimorphic tetartohedral*)

Tetragonal pyramids	$\{hkl\}, \{khl\}, \{h\bar{k}l\}, \{k\bar{h}l\}$
Tetragonal pyramids	$\{hhl\}, \{h\bar{h}l\}, \{h0l\}, \{h\bar{0}l\}$
Tetragonal prisms	$\{hk0\}, \{k\bar{h}0\}; \{110\}, \{100\}$
Pedions	$\{001\}, \{00\bar{1}\}$

Wulfenite,  $\text{PbMoO}_4$ , may perhaps belong to this class. Crystals like Fig. 131 have been found but etch-figures indicate the tetrag-

onal bipyramidal class. The artificial compound,  $\text{Ba}(\text{SbO})_2 \cdot (\text{C}_4\text{H}_4\text{O}_6)_2 \cdot \text{H}_2\text{O}$ , certainly belongs here.

#### TETRAGONAL BISPHENOIDAL CLASS. $\bar{A}_4$

(*Sphenoidal tetartohedral*)

The crystals of this class have composite symmetry with respect to a four-fold axis and a plane normal to it.

Tetragonal bisphenoids	$\{hkl\}$ , $\{khl\}$ ; $\{hhl\}$ , $\{h\bar{h}l\}$ ; $\{h0l\}$ , $\{0kl\}$
Tetragonal prisms	$\{hk0\}$ , $\{kh0\}$ ; $\{110\}$ , $\{100\}$
Pinacoid	$\{001\}$

An artificial compound,  $\text{Ca}_2\text{Al}_2\text{SiO}_7$ , has been assigned to this class by Weyberg (1906).

### 10. THE HEXAGONAL SYSTEM<sup>1</sup>

The hexagonal system includes all crystals which can be referred

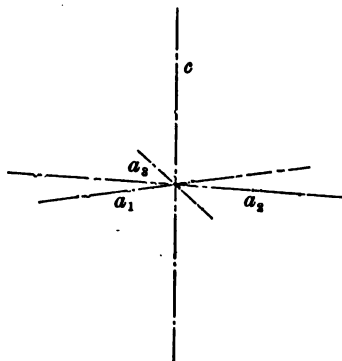


FIG. 132.—Hexagonal axes.

to four axes, three interchangeable ones in a plane at right angles to the fourth. The positive ends of the three lateral axes make angles of  $120^\circ$  with each other as shown in Fig. 132. The index on the third axis is designated by  $i$ , so that the Miller symbol for the general form is  $\{hk\bar{i}l\}$ , in which  $h+k=i$ . The axes may be designated  $a_1:a_2:a_3:c$ , in which  $a_1$ ,  $a_2$ , and  $a_3$  are unity and  $c$  either greater or less than unity. The axis of 3-fold

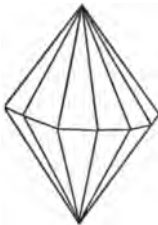
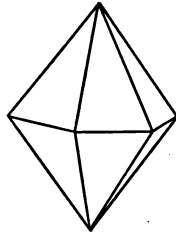
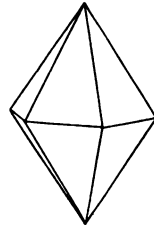
or 6-fold symmetry is always taken as the  $c$ -axis.

<sup>1</sup>Twelve crystal classes are assigned to this system. They are sometimes treated under two systems, the trigonal and the hexagonal. As there are three different methods of subdivision, upon which there is no general agreement, it is preferable to consider them all under one system.

**Dihexagonal Bipyramidal Class.  $A_6 \cdot 6A_2 \cdot 7P \cdot (C)$** *(Holohedral)*

<b>Dihexagonal bipyramid</b>	24 faces $\{hk\bar{l}\}$	(Dihexagonal pyramid)
<b>Hexagonal bipyramid</b>	12 faces $\{h \cdot h \cdot 2\bar{h} \cdot l\}$	(Pyramid of 2d order)
<b>Hexagonal bipyramid</b>	12 faces $\{h0\bar{h}l\}$	(Pyramid of 1st order)
<b>Dihexagonal prism</b>	12 faces $\{hk\bar{l}0\}$	(Dihexagonal prism)
<b>Hexagonal prism</b>	6 faces $\{11\bar{2}0\}$	(Prism of 2d order)
<b>Hexagonal prism</b>	6 faces $\{10\bar{1}0\}$	(Prism of 1st order)
<b>Pinacoid</b>	2 faces $\{0001\}$	(Basal pinacoid)

**Dihexagonal Bipyramid  $\{hk\bar{l}\}$**  (Dihexagonal pyramid). This form consists of 24 faces (scalene triangles in the ideal form) cutting the four axes at unequal distances. The angles over alternate polar edges are equal. (Fig. 133.)

FIG. 133  $\{hk\bar{l}\}$ .FIG. 134  $\{h \cdot h \cdot 2\bar{h} \cdot l\}$ .FIG. 135  $\{h0\bar{h}l\}$ .

**Hexagonal Bipyramid  $\{h \cdot h \cdot 2\bar{h} \cdot l\}$**  (Pyramid of the second order). The faces cut two of the lateral axes at equal but greater distances than the third lateral axis. (Fig. 134.)

**Hexagonal Bipyramid  $\{h0\bar{h}l\}$**  (Pyramid of the first order). The faces cut two of the lateral axes, but are parallel to the third. (Fig. 135.) This form differs from  $\{h \cdot h \cdot 2\bar{h} \cdot l\}$  only in position.

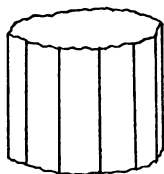
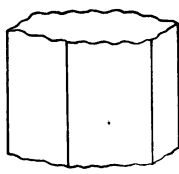
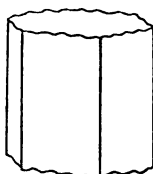
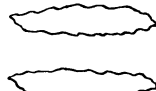
**Dihexagonal Prism  $\{hk\bar{l}0\}$** . All the faces are in a vertical zone, each being parallel to the vertical axis. Alternate angles are equal. (Fig. 136.)

**Hexagonal Prism  $\{11\bar{2}0\}$**  (Prism of the second order). This form consists of six faces making angles of  $60^\circ$  with each other. (Fig. 137.)



**Hexagonal Prism  $\{10\bar{1}0\}$**  (Prism of the first order). This is similar to  $\{11\bar{2}0\}$  except in position. (Fig. 138.)

**Pinacoid  $\{0001\}$**  (Basal pinacoid). This form consists of two opposite parallel faces. (Fig. 139.)

FIG. 136.  $\{hkil0\}$ .FIG. 137.  $\{11\bar{2}0\}$ .FIG. 138.  $\{10\bar{1}0\}$ .FIG. 139.  $\{0001\}$ .

**Combinations.** The habit is prismatic, pyramidal, or tabular. Simple combinations are the rule in this class. As beryl is the only common mineral belonging to this class, it is the only example given for practice.

#### Example

**Beryl.**  $c=0.498$ . Usual forms:  $c\{0001\}$ ,  $m\{10\bar{1}0\}$ ,  $p\{10\bar{1}1\}$ ,  $s\{11\bar{2}1\}$ ,  $v\{21\bar{3}1\}$ . Interfacial angles:  $mm(10\bar{1}0:01\bar{1}0)=60^\circ 0'$ ;  $cs(0001:11\bar{2}1)=44^\circ 56'$ ;  $cp(0001:10\bar{1}1)=29^\circ 57'$ ;  $mv(10\bar{1}0:21\bar{3}1)$

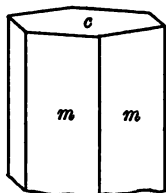


FIG. 140.

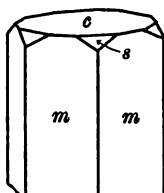


FIG. 141.

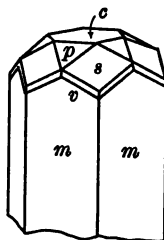


FIG. 142.

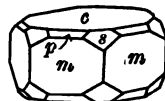


FIG. 143.

$=37^\circ 49'$ ;  $ms(10\bar{1}0:11\bar{2}1)=52^\circ 17'$ . Figs. 140 and 141 are the ordinary combinations. Fig. 142 has in addition the general form  $v\{21\bar{3}1\}$ . Fig. 143 represents beryl of tabular habit, which is rare as compared with the prismatic habit.

DIHEXAGONAL PYRAMIDAL CLASS.  $A_6 \cdot 6P$ *(Hemimorphic hemihedral)*

Dihexagonal pyramids	$\{hk\bar{i}l\}$ , $\{hk\bar{i}\bar{l}\}$
Hexagonal pyramids	$\{h \cdot h \cdot 2\bar{h} \cdot l\}$ , $\{h \cdot h \cdot 2\bar{h} \cdot \bar{l}\}$ ; $\{h0\bar{h}l\}$ , $\{h0\bar{h}\bar{l}\}$
Dihexagonal prism	$\{hk\bar{i}0\}$
Hexagonal prisms	$\{10\bar{1}0\}$ , $\{11\bar{2}0\}$
Pedions	$\{0001\}$ , $\{000\bar{1}\}$

The forms in the upper half of the crystal are different from those in the lower half. This is apparent from Fig. 144, which represents iodyrite (AgI). The forms are  $c\{0001\}$ ,  $u\{40\bar{4}1\}$ ,  $a\{11\bar{2}0\}$ , and  $\pi\{40\bar{4}\bar{5}\}$ .

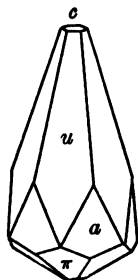


Fig. 144.

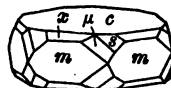


Fig. 145.

HEXAGONAL BIPYRAMIDAL CLASS.  $A_6 \cdot P \cdot C$ *(Pyramidal hemihedral)*

Hexagonal bipyramids	$\{hk\bar{i}l\}$ , $\{kh\bar{i}l\}$ ; $\{h0\bar{h}l\}$ , $\{h \cdot h \cdot 2\bar{h} \cdot l\}$
Hexagonal prisms	$\{hk\bar{i}0\}$ , $\{kh\bar{i}0\}$ ; $\{11\bar{2}0\}$ , $\{10\bar{1}0\}$
Pinacoid	$\{0001\}$

Apatite,  $\text{Ca}_5\text{F}(\text{PO}_4)_3$ , is the best example of this class. Fig. 145 represents a crystal with  $c\{0001\}$ ,  $m\{10\bar{1}0\}$ ,  $s\{11\bar{2}1\}$   $x\{10\bar{1}1\}$  and the general form  $\mu\{21\bar{3}1\}$ .

HEXAGONAL TRAPEZOHEDRAL CLASS.  $A_6 \cdot 6A_2$ *(Trapezohedral hemihedral)*

Hexagonal trapezohedrons	$\{hk\bar{i}l\}$ , $\{kh\bar{i}l\}$
Hexagonal bipyramids	$\{h \cdot h \cdot 2\bar{h} \cdot l\}$ , $\{h0\bar{h}l\}$
Dihexagonal prism	$\{hk\bar{i}0\}$
Hexagonal prism	$\{11\bar{2}0\}$ , $\{10\bar{1}0\}$
Pinacoid	$\{0001\}$

No mineral is known to belong to this class, but a complex double salt  $\text{Ba}(\text{SbO})_2(\text{C}_4\text{H}_4\text{O}_6)_2\cdot\text{KNO}_3$  is assigned to this class on the basis of the etch-figures (Fig. 146). Here the forms are  $c\{0001\}$ ,  $p\{10\bar{1}1\}$ , and  $m\{10\bar{1}0\}$ .

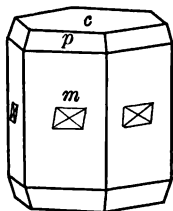


Fig. 146.

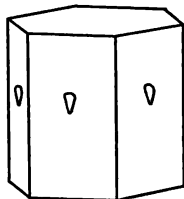


Fig. 147.

### HEXAGONAL PYRAMIDAL CLASS. $A_6$

(*Hemimorphic tetartohedral*)

Hexagonal pyramids	$\{hk\bar{l}\}$ , $\{k\bar{h}l\}$ , $\{h\bar{k}l\}$ , $\{k\bar{h}\bar{l}\}$ :
Hexagonal pyramids	$\{h0\bar{l}l\}$ , $\{h\cdot h\cdot 2\bar{h}\cdot l\}$ , $\{h0\bar{l}\bar{l}\}$ , $\{h\cdot h\cdot 2\bar{h}\cdot \bar{l}\}$
Hexagonal prisms	$\{hk\bar{i}0\}$ , $\{k\bar{h}i0\}$ ; $\{11\bar{2}0\}$ , $\{10\bar{1}0\}$
Pedions	$\{0001\}$ , $\{000\bar{1}\}$

Nepheline ( $\text{NaAlSi}_3\text{O}_8$ ) is assigned to this class because of the etch-figures represented in Fig. 147.

### Ditrigonal Scalenohedral Class. $A_6\cdot 3A_2\cdot 3P\cdot (C)$

(*Rhombohedral hemihedral*)

The lateral axes are the axes of 2-fold symmetry and the  $c$ -axis, the axis of 3-fold symmetry. The crystals of this and some other classes of the hexagonal system are sometimes referred to three interchangeable axes at oblique angles as represented in Fig. 148. In this case the Miller symbol has three indices  $hkl$  and the axial element is  $\alpha$ , the oblique angle between the axes.

Scalenohedrons	12 faces	$\{hk\bar{l}\}$ , $\{k\bar{h}l\}$ *	(Scalenohedrons)
Hexagonal bipyramid	12 faces	$\{h\cdot h\cdot 2\bar{h}\cdot l\}$	(Pyramid of 2d order)
Rhombohedrons	6 faces	$\{h0\bar{h}l\}$ , $\{0h\bar{h}l\}$	(Rhombohedrons)
Dihexagonal prism	12 faces	$\{hk\bar{i}0\}$	(Dihexagonal prism)
Hexagonal prism	6 faces	$\{10\bar{1}0\}$	(Prism of 1st order)
Hexagonal prism	6 faces	$\{11\bar{2}0\}$	(Prism of 2d order)
Pinacoid	2 faces	$\{0001\}$	(Basal pinacoid)

\* In these symbols  $h > k$ ; for example,  $\{2\bar{1}31\}$  is  $\{hk\bar{l}\}$  and  $\{12\bar{3}1\}$  is  $\{k\bar{h}l\}$ .

**Scalenohedrons**  $\{hk\bar{l}\}, \{k\bar{h}l\}$ . The general form of this class is a 12-sided figure, each face of which is a scalene triangle. There are three kinds of edges, short polar, long polar, and middle edges, each with their characteristic interfacial angles. The  $\{hk\bar{l}\}$  form is called positive and the  $\{k\bar{h}l\}$  form, negative. Fig. 149 is a positive scalenohedron.

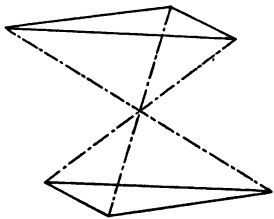
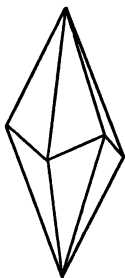
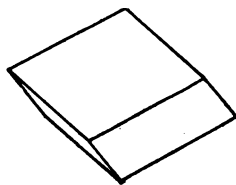


FIG. 148.

FIG. 149.  $\{hk\bar{l}\}$ .FIG. 150.  $\{h0hl\}$ .

**Hexagonal Bipyramid**  $\{h \cdot h \cdot 2\bar{h} \cdot 1\}$  (Pyramid of the second order). This form consists of twelve faces, each an isosceles triangle (Fig. 134).

**Rhombohedral**  $\{h0\bar{h}l\}, \{0h\bar{h}l\}$ . A rhombohedron consists of six rhombic faces. It is like a cube distorted in the direction of one of its diagonals. A rhombohedron is distinguished as acute or obtuse according to whether the angle over the polar edges is greater or less than  $90^\circ$ . The rhombohedron with faces in the middle front, right rear, and left rear dodecants is called positive and has the symbol  $\{h0\bar{h}l\}$ , while the rhombohedron with faces in the right front, left front, and middle rear dodecants is called negative and has the symbol  $\{0h\bar{h}l\}$ . Fig. 150 is an obtuse positive rhombohedron.

**Dihexagonal Prism**  $\{hk\bar{l}0\}$ . There are twelve faces in a vertical zone. (Fig. 136.) Alternate angles are equal.

**Hexagonal Prism**  $\{10\bar{1}0\}$  (Prism of the first order). There are six faces meeting at angles of  $60^\circ$ . (Fig. 138.)

**Hexagonal Prism  $\{11\bar{2}0\}$**  (Prism of the second order). This form is exactly like  $\{10\bar{1}0\}$  except in position (Fig. 137).

**Pinacoid  $\{0001\}$**  (Basal pinacoid). There are two faces at opposite ends of the vertical axis. (Fig. 139.)

### Example

**Calcite.**  $c=0.854$ . Usual forms:  $c\{0001\}$ ,  $m\{1010\}$ ,  $a\{11\bar{2}0\}$ ,  $e\{01\bar{1}2\}$ ,  $r\{10\bar{1}1\}$ ,  $f\{02\bar{2}1\}$ ,  $M\{40\bar{4}1\}$ ,  $v\{21\bar{3}1\}$ ,  $y\{32\bar{5}1\}$ ,  $t\{21\bar{3}4\}$ . Cleavage parallel to  $r$ . Interfacial angles:  $ee(01\bar{1}2:\bar{1}012)=45^\circ 3'$ ;  $em(01\bar{1}2:10\bar{1}0)=63^\circ 45'$ ;  $rr(10\bar{1}1:\bar{1}101)=74^\circ 55'$ ;  $rm(10\bar{1}1:10\bar{1}0)=45^\circ 23\frac{1}{2}'$ ;  $ff(02\bar{2}1:\bar{2}021)=101^\circ 9'$ ;  $fm(02\bar{2}1:01\bar{1}0)=26^\circ 53'$ ;  $MM(40\bar{4}1:\bar{4}401)=114^\circ 10'$ ;  $Mm(40\bar{4}1:10\bar{1}0)=14^\circ 13'$ ;  $vv(21\bar{3}1:\bar{2}3\bar{1}1)=75^\circ 22'$ ;  $vv(21\bar{3}1:3\bar{1}21)=35^\circ 36'$ ;  $vv(21\bar{3}1:12\bar{3}1)=47^\circ 1'$ ;  $yy(32\bar{5}1:\bar{3}5\bar{2}1)=70^\circ 59'$ ;  $yy(32\bar{5}1:5\bar{2}31)=45^\circ 32'$ ;  $vy(21\bar{3}1:32\bar{5}1)=8^\circ 53'$ ;  $rv(10\bar{1}1:21\bar{3}1)=29^\circ 1\frac{1}{2}'$ ;  $mv(10\bar{1}0:21\bar{3}1)=28^\circ 4'$ ;  $tt(21\bar{3}4:3\bar{1}24)=20^\circ 36\frac{1}{2}'$ ;  $te(21\bar{3}4:01\bar{1}2)=20^\circ 57\frac{1}{2}'$ .

Figs. 151–162 represent some of the common types of calcite crystals. The dotted lines in the figures represent cleavage planes which aid in the determination.

## Ditrigonal Pyramidal Class. $A_3\cdot 3P$

### (Hemimorphic tetartohedral)

The lateral axes are diagonal to the planes of symmetry.

Ditrigonal pyramids	$\{hk\bar{l}\}$ , $\{hk\bar{l}\}$	(Hemimorphic pyramids)
“ “	$\{kh\bar{l}\}$ , $\{kh\bar{l}\}$	“ “
Hexagonal pyramids	$\{h\cdot h\cdot 2\bar{h}\cdot 1\}$ , $\{h\cdot h\cdot 2\bar{h}\cdot 1\}$	(Hemimorphic pyramids)
Trigonal pyramids	$\{h0\bar{h}l\}$ , $\{h0\bar{h}l\}$	(Pyramids of 1st order)
“ “	$\{0h\bar{h}l\}$ , $\{0h\bar{h}l\}$	“ “ “
Ditrigonal prisms	$\{hk\bar{l}0\}$ , $\{kh\bar{l}0\}$	(Ditrigonal prisms)
Hexagonal prism	$\{11\bar{2}0\}$	(Prism of 2d order)
Trigonal prisms	$\{10\bar{1}0\}$ , $\{01\bar{1}0\}$	(Prisms of 1st order)
Pedions	$\{0001\}$ , $\{000\bar{1}\}$	(Basal planes)

**Ditrigonal Pyramids  $\{hk\bar{l}\}$ ,  $\{hk\bar{l}\}$ ,  $\{kh\bar{l}\}$ ,  $\{kh\bar{l}\}$**  (Hemimorphic ditrigonal pyramids). The general form is a six-faced pyramid with alternate angles equal. There are positive and

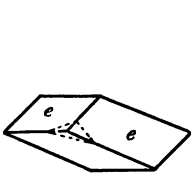


FIG. 151

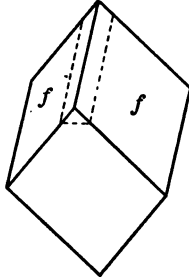


FIG. 152.

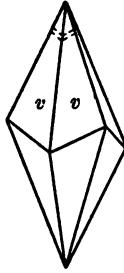


FIG. 153.

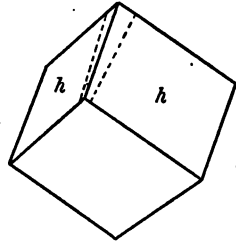


FIG. 154.

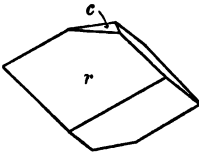


FIG. 155.

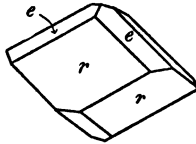


FIG. 156.

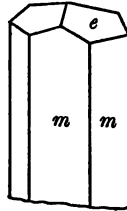


FIG. 157.

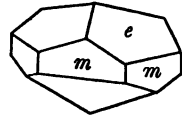


FIG. 158

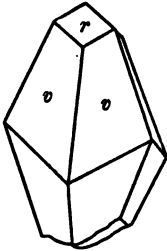


FIG. 159.

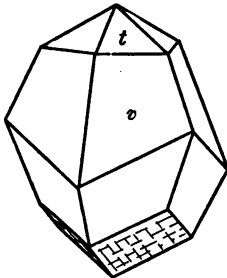


FIG. 160.

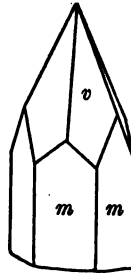


FIG. 161.

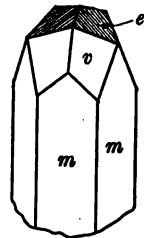


FIG. 162.

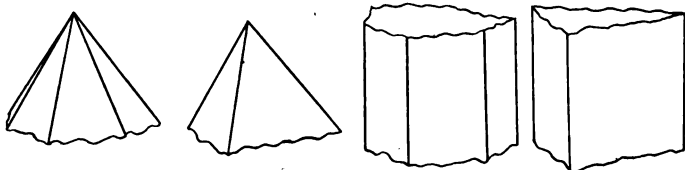
FIGS. 151-162.—Calcite Crystals.

negative and upper and lower forms as indicated by the symbols. Fig. 163.

**Hexagonal Pyramids**  $\{h \cdot h \cdot 2\bar{h} \cdot 1\}$ ,  $\{h \cdot h \cdot 2\bar{h} \cdot 1\}$  (Hemimorphic hexagonal pyramids). There are six faces each cutting two lateral axes at equal but greater distances than the third lateral axis.

**Trigonal Pyramids**  $\{h0\bar{h}1\}$ ,  $\{h0\bar{h}1\}$ ,  $\{0h\bar{h}1\}$ ,  $\{0h\bar{h}1\}$  (Hemimor-

phic trigonal pyramids of the first order). Each of these forms consists of three faces. They are distinguished as positive and negative and upper and lower. Fig. 164 represents an upper negative trigonal pyramid.

FIG. 163.  $\{hk\bar{l}\}$ .FIG. 164.  $\{h\bar{o}k\}$ .FIG. 165.  $\{\pm 1\bar{2}0\}$ .FIG. 166.  $\{10\bar{1}1\}$ .

**Ditrigonal Prisms  $\{hk\bar{l}0\}$ ,  $\{khl\bar{0}\}$ .** The angles over alternate angles are equal. Fig. 165.

**Hexagonal Prism  $\{11\bar{2}0\}$ , (Second order prism).**

**Trigonal Prisms  $\{10\bar{1}0\}$ ,  $\{01\bar{1}0\}$ .** These two forms differ only in position. Fig. 166.

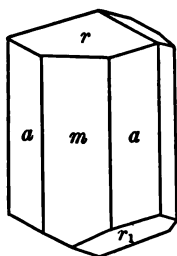


FIG. 167.

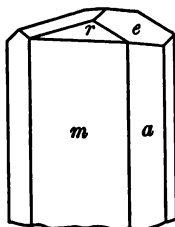


FIG. 168.

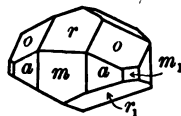


FIG. 169.

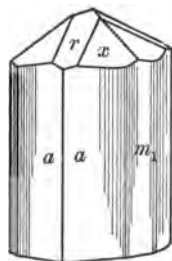


FIG. 170.

**Pedions  $\{0001\}$ ,  $\{000\bar{1}\}$ .** Each of these forms consists of a single face, one at the upper end of the crystal and the other at the lower end.

Tourmaline, a complex boro-silicate, is the best representative of this class.

#### Example

**Tourmaline.**  $c=0.447$ . Usual forms:  $m\{10\bar{1}0\}$ ,  $m_1\{01\bar{1}0\}$ ,  $a\{11\bar{2}0\}$ ,  $r\{10\bar{1}1\}$ ,  $r_1\{01\bar{1}1\}$ ,  $o\{02\bar{2}1\}$ ,  $e\{01\bar{1}2\}$ ,  $x\{12\bar{3}2\}$ . Interfacial angles:  $rr(10\bar{1}1:\bar{1}101)=46^\circ 52'$ ;  $mr(10\bar{1}0:10\bar{1}1)=62^\circ 40'$ ;

$ee(01\bar{1}2:\bar{1}012)=25^\circ 2'$ ;  $em_1(01\bar{1}2:01\bar{1}0)=75^\circ 30\frac{1}{2}'$ ;  $oo(02\bar{2}1:\bar{2}021)=77^\circ 0'$ ;  $om_1(02\bar{2}1:01\bar{1}0)=44^\circ 3'$ ;  $xx(12\bar{3}2:\bar{1}3\bar{2}2)=21^\circ 18'$ ;  $xx(12\bar{3}2:3\bar{2}12)=43^\circ 22\frac{1}{2}'$ . Figs. 167 to 170 represent typical crystals of tourmaline.

### TRIGONAL TRAPEZOHEDRAL CLASS. $A_3\cdot 3A_2$

#### (*Trapezohedral tetartohedral*)

The axes of symmetry are the axes of reference.

Trigonal trapezohedrons	$\{hk\bar{l}\}$ , $\{k\bar{h}l\}$
Trigonal bipyramid;	$\{h\cdot h\cdot 2\bar{h}\cdot l\}$
Rhombohedral	$\{h0\bar{h}l\}$ , $\{0h\bar{h}l\}$
Trigonal prisms	$\{11\bar{2}0\}$ , $\{\bar{1}210\}$
Ditrigonal prisms	$\{hk\bar{i}0\}$ , $\{k\bar{h}i0\}$
Hexagonal prism	$\{10\bar{1}0\}$
Pinacoid	$\{0001\}$

**Quartz**,  $\text{SiO}_2$ , and cinnabar,  $\text{HgS}$ , are the only known minerals belonging to this class. The general form is comparatively rare and always occurs as a subordinate form. The forms  $\{hk\bar{l}\}$  and  $\{k\bar{h}l\}$  are distinguished as right-handed and left-handed forms respectively. Fig. 171 represents a right-handed quartz crystal with the forms  $m\{10\bar{1}0\}$ ,  $r\{10\bar{1}1\}$ ,  $z\{01\bar{1}1\}$ ,  $s\{11\bar{2}1\}$ , and  $x\{51\bar{6}1\}$ . Figs. 375 and 376, page 152, show a right-handed crystal and a left-handed crystal side by side. For angles of quartz see page 305.

### TRIGONAL RHOMBOHEDRAL CLASS. $\bar{A}_6(C)$

#### (*Rhombohedral tetartohedral*)

Rhombohedral	$\{hk\bar{l}\}$ , $\{k\bar{h}l\}$ , $\{i\bar{k}hl\}$ , $\{\bar{k}ihl\}$
Rhombohedral	$\{h\cdot h\cdot 2\bar{h}\cdot l\}$ , $\{2h\cdot h\cdot \bar{h}\cdot l\}$
Rhombohedral	$\{h0\bar{h}l\}$ , $\{0h\bar{h}l\}$
Hexagonal prisms	$\{hk\bar{i}0\}$ , $\{k\bar{h}i0\}$
Hexagonal prism	$\{11\bar{2}0\}$
Hexagonal prism	$\{10\bar{1}0\}$
Pinacoid	$\{0001\}$

Phenacite,  $\text{Be}_2\text{SiO}_4$ , is a representative of this class. Fig. 172 is a simple combination with  $a\{11\bar{2}0\}$  and  $x\{21\bar{3}2\}$ .



TRIGONAL BIPYRAMIDAL CLASS.  $A_3P$ *(Sphenoidal tetartohedral)*

Trigonal bipyramids	$\{hk\bar{l}\}, \{kh\bar{l}\}$
Trigonal prisms	$\{hk\bar{2}0\}, \{k\bar{h}20\}$
Hexagonal prism	$\{11\bar{2}0\}$
Trigonal prisms	$\{10\bar{1}0\}, \{01\bar{1}0\}$
Trigonal bipyramids	$\{h\cdot h\cdot 2\bar{h}\cdot l\}, \{2h\cdot \bar{h}\cdot \bar{h}\cdot l\}$
Trigonal bipyramids	$\{h0\bar{h}l\}, \{0h\bar{h}l\}$
Pinacoid	$\{0001\}$

This is the only class for which no example has yet been found. The forms given above may be predicted from the symmetry.

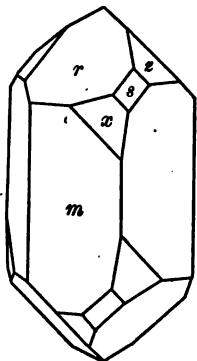


FIG. 171.

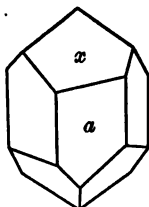


FIG. 172.

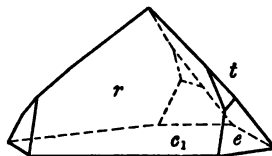


FIG. 173.

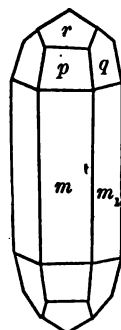


FIG. 174.

TRIGONAL PYRAMIDAL CLASS.  $A_3$ *(Ogdohedral)*

Trigonal pyramids	$\{hk\bar{l}\}, \{kh\bar{l}\}, \{i\bar{k}\bar{h}l\}, \{\bar{k}i\bar{h}l\};$
Trigonal pyramids	$\{hk\bar{l}\}, \{kh\bar{l}\}, \{i\bar{k}\bar{h}l\}, \{\bar{k}i\bar{h}l\}$
Trigonal pyramids	$\{h\cdot h\cdot 2\bar{h}\cdot l\}, \{h\cdot h\cdot 2\bar{h}\cdot l\}, \{2h\cdot \bar{h}\cdot \bar{h}\cdot l\}, \{2h\cdot \bar{h}\cdot \bar{h}\cdot l\}$
Trigonal pyramids	$\{h0\bar{h}l\}, \{h0\bar{h}l\}; \{0h\bar{h}l\}, \{0h\bar{h}l\}$
Trigonal prisms	$\{hk\bar{2}0\}; \{k\bar{h}20\}; \{11\bar{2}0\}, \{1\bar{2}10\}$
Trigonal prisms	$\{10\bar{1}0\}, \{01\bar{1}0\}$
Pedions	$\{0001\}, \{000\bar{1}\}$

Hydrous sodium periodate,  $\text{NaIO}_4 \cdot 3\text{H}_2\text{O}$ , belongs to this

class. Fig. 173 represents a crystal with the forms  $r\{10\bar{1}1\}$ ,  $e\{02\bar{2}1\}$ ,  $c_1\{000\bar{1}\}$ , and  $t\{5\cdot4\cdot9\cdot10\}$ . (After Pakle.)

### DITRIGONAL BIPYRAMIDAL CLASS. $A_3\cdot3A_2\cdot4P(C)$

(*Sphenoidal hemihedral*)

Ditrigonal bipyramids	$\{hk\bar{l}\}$ , $\{kh\bar{l}\}$
Hexagonal bipyramid	$\{h\cdot h\cdot2\bar{h}\cdot l\}$
Trigonal bipyramids	$\{h0\bar{h}l\}$ , $\{0h\bar{h}l\}$
Ditrigonal prisms	$\{hk\bar{i}0\}$ $\{kh\bar{i}0\}$
Hexagonal prism	$\{11\bar{2}0\}$
Trigonal prisms	$\{10\bar{1}0\}$ , $\{01\bar{1}0\}$
Pinacoid	$\{0001\}$

Acid silver phosphate,  $Ag_2HPO_4$ , has been assigned to this class by Dufet. Fig. 174 represents a crystal with the forms  $m\{10\bar{1}0\}$ ,  $m_1\{01\bar{1}0\}$ ,  $r\{10\bar{1}1\}$ ,  $p\{20\bar{2}1\}$ , and  $q\{02\bar{2}1\}$ . Benitoite,  $BaTiSi_3O_{10}$ , a mineral from San Benito County, California, described by Louderback was also assigned to this class, but according to Ježek it belongs to the ditrigonal pyramidal class.

## 11. ISOMETRIC SYSTEM

This system includes all crystals that can be referred to three interchangeable axes at right angles. The axes may be designated  $a_1$ ,  $a_2$ , and  $a_3$  as in Fig. 175. The five classes of the isometric system have four axes of 3-fold symmetry in common. The cube and the dodecahedron occur in all five classes. The angles of the corresponding forms in all crystals are equal.

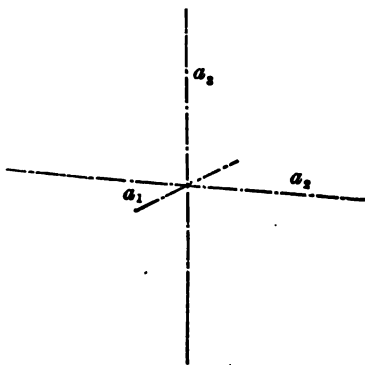


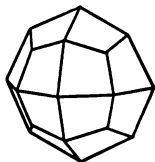
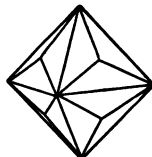
FIG. 175.—Isometric axes.

**Isometric Hexoctahedral Class. 6A, 4A, 3A, 9P(C)***(Holohedral)*

The crystals of this class have the maximum degree of symmetry possible in crystals. The four-fold axes of symmetry are the axes of reference.

<b>Hexoctahedron</b>	48 faces	{ <i>hkl</i> }
<b>Trapezohedron</b>	24 faces	{ <i>hkk</i> }
<b>Trisoctahedron</b>	24 faces	{ <i>hhl</i> }
<b>Tetrahexahedron</b>	24 faces	{ <i>hko</i> }
<b>Dodecahedron</b>	12 faces	{ <i>110</i> }
<b>Octahedron</b>	8 faces	{ <i>111</i> }
<b>Cube</b>	6 faces	{ <i>100</i> }

**Hexoctahedron** {*hkl*}. The general form consists of forty-eight faces, the symbols of which may be derived from the form symbol by taking six permutations of letters and eight permutations of signs. Fig. 176 represents the hexoctahedron {321}.

FIG. 176. {*hkl*}.FIG. 177. {*hkk*}.FIG. 178. {*hhl*}.

**Trapezohedron** {*hkk*}. Each face is a trapezoid. This form is sometimes called the tetragonal trisoctahedron to distinguish it from the next mentioned form, the trigonal trisoctahedron. Fig. 177 represents the form {211} which is common on garnet, leucite, and analcite.

**Trisoctahedron** {*hhl*}. Each face is an isosceles triangle. With this form the intercept on the third axis is *greater* than the intercepts upon the other two which are equal, while with {*hkk*} the intercept on the third axis is *less* than the intercepts upon the other two. Fig. 178 represents the trisoctahedron {221}.

**Tetrahexahedron {hk0}.** This form is so called because it apparently consists of a four-faced pyramid on each cube face. Fig. 179 represents the form {210}.

**Dodecahedron {110}.** This form (Fig. 180) consists of twelve faces, each rhombic in shape. The interfacial angles are  $60^\circ$  and  $90^\circ$ .

**Octahedron {111}.** As its name implies, this is an eight-faced form. Each face is an equilateral triangle. The interfacial angles are  $70^\circ 32'$ . (Fig. 181.)

**Cube {100}.** The cube or hexahedron is a six-faced form with interfacial angles of  $90^\circ$ . (Fig. 182.)

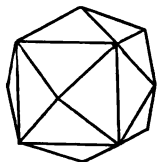


FIG. 179. {hk0}.

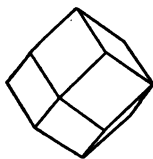


FIG. 180 {110}.

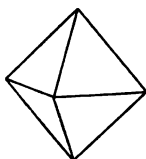


FIG. 181. {111}.

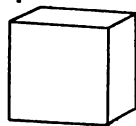


FIG. 182. {100}.

**Combinations.** The cube, octahedron, and dodecahedron are much more common than the other forms. They occur alone and in combination with each other. See Figs. 441–4 page 309. The hexoctahedron, trisoctahedron, and tetrahexahedron usually occur as small faces modifying simple forms. Although quite varied in aspect, isometric crystals, unless much distorted, are of about equal dimensions in all directions and this fact aids in their identification.

Galena, garnet, and fluorite are given as typical examples for study and practice.

### Examples

**Galena.** Usual forms:  $a\{100\}$ ,  $o\{111\}$ . Interfacial angles:  $aa(100:010) = 90^\circ 0'$ ;  $oo(111:\bar{1}\bar{1}1) = 70^\circ 32'$ ;  $ao(100:111) =$

54° 44'. Figs. 183 to 187 represent usual combinations varying from the cube alone to the octahedron alone.

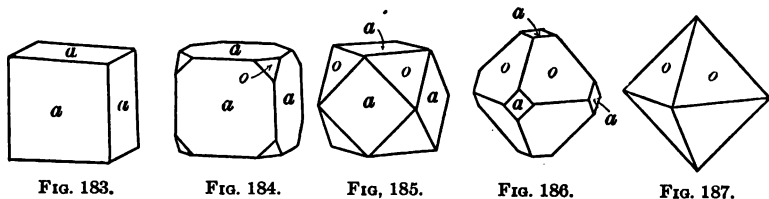


FIG. 183.

FIG. 184.

FIG. 185.

FIG. 186.

FIG. 187.

**Garnet.** Usual forms:  $d\{110\}$ ,  $n\{211\}$ . Interfacial angles:  $dd\{110:101\}=60^\circ 0'$ ;  $nn\{211:121\}=33^\circ 33\frac{1}{2}'$ ;  $nn\{211:2\bar{1}1\}=48^\circ 11\frac{1}{2}'$ ;  $dn\{110:211\}=30^\circ 0'$ . Figs. 188 to 191 represent usual combinations varying from the dodecahedron alone to the trapezohedron alone.

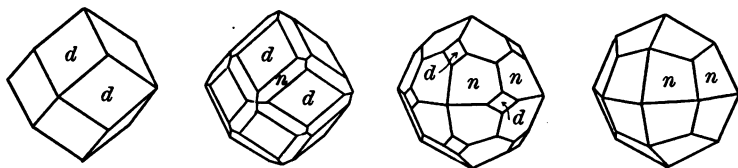


FIG. 188.

FIG. 189.

FIG. 190.

FIG. 191.

**Fluorite.** Usual forms:  $a\{100\}$ ,  $f\{310\}$ ,  $t\{421\}$ . Cleavage parallel to  $\{111\}$ . Interfacial angles:  $aa\{100:010\}=90^\circ$ ;  $af\{100:310\}=18^\circ 26'$ ;  $at\{100:421\}=29^\circ 12'$ . Figs. 192 to 195

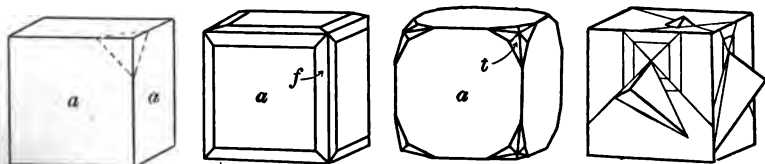


FIG. 192.

FIG. 193.

FIG. 194.

FIG. 195.

represent frequent combinations. The plane formed by the dotted lines in Fig. 192 represents octahedral cleavage. Fig.

195 represents a twin crystal in which two cubes are twinned about a cube diagonal.

### Isometric Diploidal Class. $3A_2, 4A_2, 6P(C)$

(*Pentagonal hemihedral*)

The axes of 2-fold symmetry are the axes of reference.

Diploids	24 faces	$\{hkl\}$ , $\{khl\}$
Trapezohedron	24 faces	$\{hkk\}$
Trisoctahedron	24 faces	$\{hhl\}$
Pyritohedrons	12 faces	$\{hk0\}$ , $\{kh0\}$
Dodecahedron	12 faces	$\{110\}$
Octahedron	8 faces	$\{111\}$
Cube	6 faces	$\{100\}$

Of these forms, all but the diploid and pyritohedron are geometrically similar to those of the preceding class.

**Diploids**  $\{hkl\}$ ,  $\{khl\}$ . The general form is a 24-faced form, the faces of which lie in pairs astride the planes of symmetry hence the name, which means double. The two forms  $\{hkl\}$  and  $\{khl\}$ , which are congruent, are distinguished as positive and negative. Fig. 196 represents the positive diploid  $\{321\}$ .

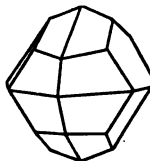


FIG. 196.  $\{hkl\}$ .

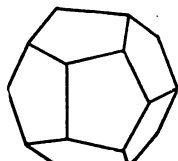


FIG. 197.  $\{khl\}$ .

**Pyritohedrons**  $\{hk0\}$ ,  $\{kh0\}$ . The pyritohedron is so named because it is common on the mineral pyrite. The two forms given are distinguished as positive and negative. On pyrite the most common form is the positive pyritohedron  $\{210\}$ , represented by Fig. 197.

#### Examples.

**Pyrite.** Usual forms:  $a\{100\}$ ,  $e\{210\}$ ,  $o\{111\}$ ,  $s\{321\}$ ,  $n\{211\}$ . Interfacial angles:  $ae(100:210) = 26^\circ 34'$ ;  $ee(210:2\bar{1}0) = 53^\circ 8'$ ;  $ee(210:102) = 66^\circ 25'$ ;  $eo(210:111) = 39^\circ 14'$ ;  $ao(100:111) = 54^\circ 44'$ ;  $se(321:210) = 17^\circ 1\frac{1}{2}'$ ;  $sa(321:100) = 36^\circ 42'$ ;  $so(321:111) = 22^\circ$

$12\frac{1}{2}^\circ$ ;  $an(100:211)=35^\circ 16'$ ;  $on(111:211)=19^\circ 28'$ ; Figs. 198 to 205 represent common types of pyrite crystals. The cube faces are usually striated as in Fig. 198.

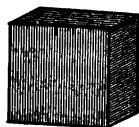


FIG. 198.

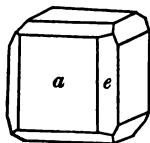


FIG. 199.

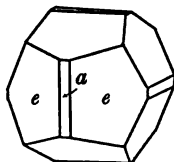


FIG. 200.

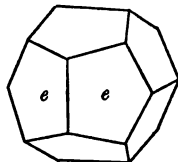


FIG. 201.

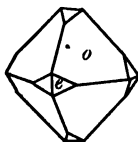


FIG. 202.

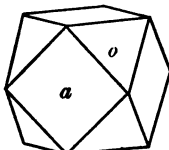


FIG. 203.

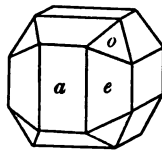


FIG. 204.

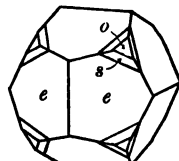


FIG. 205.

FIGS. 198-205.—Pyrite Crystals.

### Isometric Hextetrahedral Class, $3A_2, 4A_3, 6P$

(*Tetrahedral hemihedral*)

The axes of 2-fold symmetry are the axes of reference.

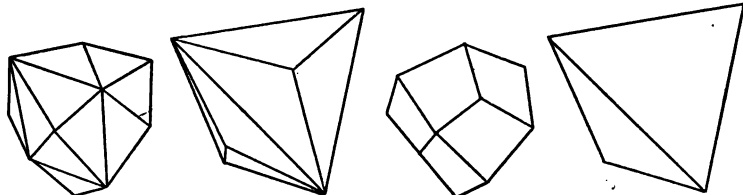
<b>Hextetrahedrons</b>	24 faces	$\{hkl\}$ , $\{h\bar{k}l\}$
<b>Tristetrahedrons</b>	12 faces	$\{hkk\}$ , $\{h\bar{k}k\}$
<b>Deltohedrons</b>	12 faces	$\{hhl\}$ , $\{h\bar{h}l\}$
<b>Tetrahedrons</b>	4 faces	$\{111\}$ , $\{1\bar{1}1\}$
<b>Tetrahexahedron</b>	24 faces	$\{hk0\}$
<b>Dodecahedron</b>	12 faces	$\{110\}$
<b>Cube</b>	6 faces	$\{100\}$

The first four forms are geometrically different from the corresponding forms in the hexoctahedral class and are described below.

**Hextetrahedrons**  $\{hkl\}$ ,  $\{h\bar{k}l\}$ . This 24-faced form is called the hextetrahedron as it apparently consists of a 6-faced pyramid built upon each face of a tetrahedron. (Fig. 206.) The two forms given are distinguished as positive and negative. They occur in alternate octants.

**Tristetrahedrons**  $\{hkk\}$ ,  $\{h\bar{k}k\}$ . These forms resemble three-faced pyramids built upon each tetrahedral face, hence the name. The two forms, which occur in alternate octants, are distinguished as positive and negative. Fig. 207 is a positive form.

**Deltohedrons**  $\{hhl\}$ ,  $\{h\bar{h}l\}$ . These two forms are also positive and negative according to the octant in which they occur. Fig. 208 represents a positive form. The name refers to the shape of the faces.

FIG. 206.  $\{hkl\}$ .FIG. 207.  $\{hkk\}$ .FIG. 208.  $\{hhl\}$ .FIG. 209.  $\{111\}$ .

**Tetrahedrons**  $\{111\}$ ,  $\{\bar{1}\bar{1}1\}$ . This is the regular tetrahedron of geometry, the interfacial angles being  $109^\circ 28'$  (Fig. 209). Like the previously mentioned forms, the positive and negative forms are exactly alike except in position. The two forms  $\{111\}$  and  $\{\bar{1}\bar{1}1\}$  in equal combination constitute an octahedron and therefore are called complementary.

**Combinations.** Crystals of this class usually have a tetrahedral aspect.

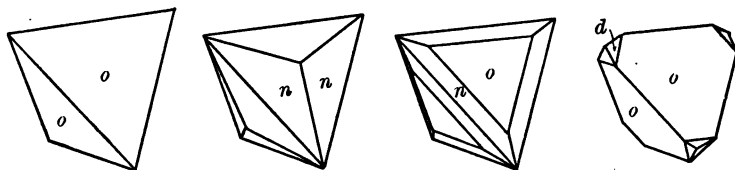


FIG. 210.

FIG. 211.

FIG. 212.

FIG. 213.

FIGS. 210-213.—Tetrahedrite.

### Example

**Tetrahedrite.** Usual forms:  $o\{111\}$ ,  $o_1\{\bar{1}\bar{1}1\}$ ,  $n\{211\}$ ,  $d\{110\}$ . Interfacial angles:  $oo(111:\bar{1}\bar{1}1) = 109^\circ 28'$ ;  $nn(211:121) = 33^\circ$



$33\frac{1}{2}^\circ$ ;  $no(211:111) = 19^\circ 28'$ ;  $do(110:111) = 35^\circ 16'$ . Figs. 210 to 213 represent usual types of tetrahedrite crystals.

Boracite, Fig. 508, page 366 is also a good example of this class.

### ISOMETRIC GYROIDAL CLASS. $6A_2 \cdot 4A_3 \cdot 3A_4$

(*Gyroidal hemihedral*)

The axes of 4-fold symmetry are the axes of reference.

The only form geometrically different from those of the hexoctahedral class is the general form, which is called a gyroid. The two forms  $\{hkl\}$  and  $\{h\bar{k}l\}$  are enantiomorphous and are distinguished as right and left.

Sylvite, KCl, and sal-ammoniac,  $NH_4Cl$ , crystallize in this class. Fig. 214 represents a crystal of  $NH_4Cl$  with the form  $\{943\}$ .

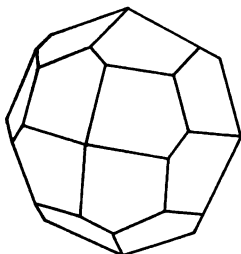


FIG. 214.—Gyroid.

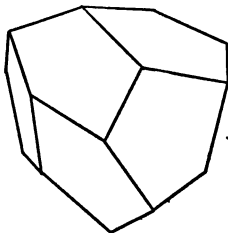


FIG. 215.—Tetartoid.

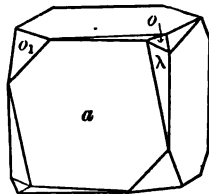


FIG. 216.

### ISOMETRIC TETARTOIDAL CLASS. $3A_2 \cdot 4A_3$

(*Tetartohedral*)

The forms in this class are the tetartoid, the tristetrahedron, the deltohedron, the pyritohedron, the dodecahedron, the tetrahedron, and the cube.

The only geometrically new form, the tetartoid, has twelve faces. There are four kinds of tetartoids possible:  $\{hkl\}$ ,  $\{khl\}$ ,  $\{h\bar{k}l\}$ ,  $\{k\bar{h}l\}$ . Fig. 215 represents the form  $\{321\}$ . Ullmannite,  $NiSbS$ , has been placed in this class because for this mineral  $\{210\}$

is a pyritohedron and  $\{111\}$  a tetrahedron. Fig. 216 represents a crystal of  $\text{Ba}(\text{NO}_3)_2$  with  $a\{100\}$ ,  $o\{111\}$ ,  $o_1\{1\bar{1}1\}$ , and the general form,  $\lambda\{421\}$ .

## 12. TWIN-CRYSTALS

Loose isolated crystals are comparatively rare in nature. Crystals are usually grouped in parallel position or in the most irregular manner. A discussion of these cases will occupy the next section.

A peculiar sort of grouping is known as **twinning** and crystals so grouped are called **twin-crystals**. Many crystals are found to be composed of two parts, one half of which has *apparently* been

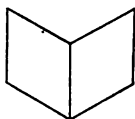


FIG. 217.

Contact twin.

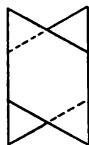


FIG. 218.

Penetration twin.

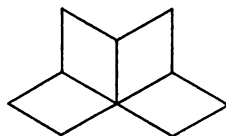


FIG. 219.

Cyclic twin.

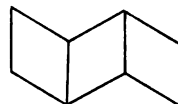


FIG. 220.

Polysynthetic twin.

revolved  $180^\circ$  about a line called the **twin-axis**. The plane normal to this axis is called the **twin-plane**. The face of union of the two individuals is called the **composition-face**. It may or may not be the twin-plane. The twin-plane is always a crystal face or a possible crystal face, but never a plane of symmetry. The twin-axis is always a possible crystal edge or is normal to a possible crystal face, but it is never an axis of even symmetry.

Twin crystals are distinguished as (1) **contact twins** in which case the composition face is definite or as (2) **penetration twins** in which the composition face is irregular. Fig. 217 represents a contact twin and Fig. 218, a penetration twin. In the case of contact twins the **twin-law** is defined with respect to a twin-plane, while in penetration twins it is defined with respect to a twin-axis.

Twins are usually recognized by the presence of reëntrant angles, but there are exceptions to this general rule.

In addition to twins composed of two individuals, there are also multiple twins made up of three or more parts. If the same face serves as twin-plane for a series of individuals we have a **poly-synthetic twin** (Fig. 220). But if different faces (of the same form) are twin-planes we have a **cyclic twin** (Fig. 219).

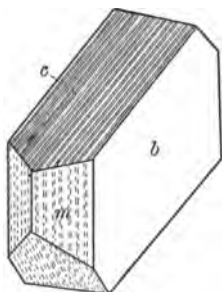


FIG. 221.—Plagioclase.

A polysynthetic twin may consist of a large number of individuals and some of these may be so narrow that they appear as striations. Cleavages of calcite and of plagioclase often show twinning striations. In calcite the rhombohedron  $\{01\bar{1}2\}$  is the twin-plane and so on the cleavage face  $\{10\bar{1}1\}$  the striations are parallel to the long diagonal as represented in Fig. 235.

In plagioclase the twin-plane is usually  $b\{010\}$ , and so the twin striations appear on the  $c\{001\}$  cleavage face as narrow bands parallel to the  $(001:010)$  edge as shown in Fig. 221.

### Examples

Fig. 222 represents a twin of gypsum with  $\{100\}$  as twinning plane. In Figs. 223 (augite) and 224 (hornblende)  $\{100\}$  is also twin-plane. Fig. 225 represents a Carlsbad twin of orthoclase. This is a penetration twin with the  $c$ -axis as twin-axis.

Fig. 226 represents a cruciform penetration twin of staurolite. In Fig. 227 a contact twin of aragonite with  $m\{110\}$  as twin-plane is shown. A penetration trilling of cerussite is illustrated by Fig. 228. Fig. 229, a twin of marcasite, apparently has an axis of 5-fold symmetry. The angles in this case would be exactly  $72^\circ$  ( $\frac{1}{5}$  of  $360^\circ$ ), but accurate measurement proves them to be  $74^\circ 55'$  instead.

Figs. 230 to 233, inclusive, represent various kinds of rutile twins, but in all cases  $(101)$  is the twin-plane. Fig. 230 is a

simple contact twin; Fig. 231 shows twin striations. A single band inserted in twinning position like Fig. 232 is called a **twin-**

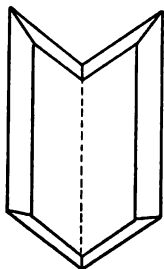


FIG. 222.

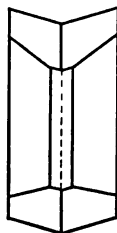


FIG. 223.

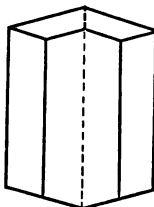


FIG. 224.

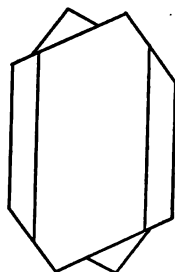


FIG. 225.

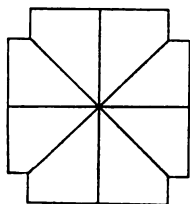


FIG. 226.

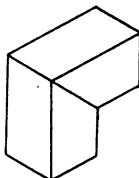


FIG. 227.

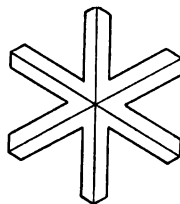


FIG. 228.

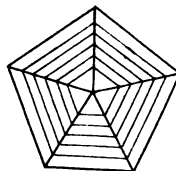


FIG. 229.

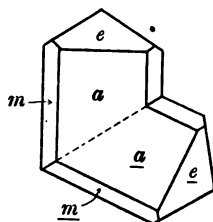


FIG. 230.

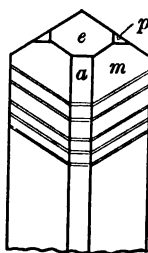


FIG. 231.

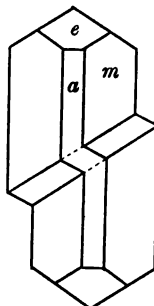


FIG. 232.

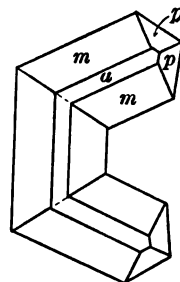


FIG. 233.

**seam.** Fig. 233 is a cyclic twin. These four figures are orthographic projections.

The next row of figures illustrates the four twin-laws known for calcite. Fig. 234 is the scalenohedron  $\{21\bar{3}1\}$  twinned on  $\{0001\}$ . Fig. 235 represents a calcite cleavage with twin lamellæ inserted parallel to  $\{01\bar{1}2\}$ , which is the most common twin-law

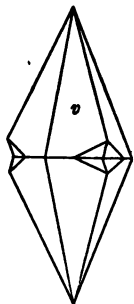


FIG. 234.

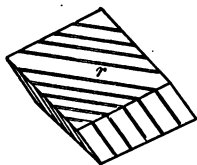


FIG. 235.

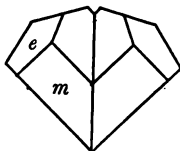


FIG. 236.

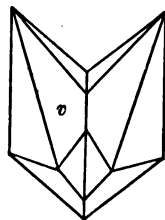


FIG. 237.

for calcite. Fig. 236 is a calcite twin with  $\{10\bar{1}1\}$  as twin-law, while Fig. 237 is a scalenohedron twinned on  $\{02\bar{2}1\}$ , the rarest of the twin-laws for calcite.

The next four figures represent twins of the isometric system. Fig. 238 (with  $111$  as twin-plane) is called the spinel twin because it is so common for the mineral spinel. Fig. 239 represents twin

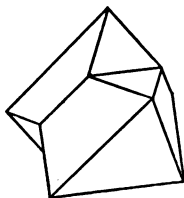


FIG. 238.

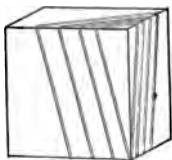


FIG. 239.

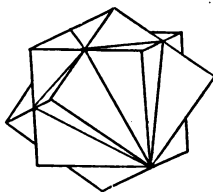


FIG. 240.

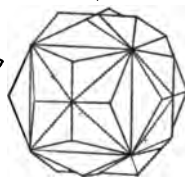


FIG. 241.

striations observed on cubic cleavages of galena. Here the twin-plane is  $\{441\}$ . A penetration twin of fluorite with the cube diagonal as twin-axis is represented in Fig. 240, while Fig. 241 is a twin of pyrite with the  $a$ -axis as twin-axis. This is known as the "eiseneres Kreuz."

The tendency of twinning is to apparently raise the grade of symmetry. This is especially the case with pseudo-hexagonal orthorhombic minerals such as chrysoberyl, aragonite, witherite, and cerussite. See Figs. 460, 492, 493, and 497.

### 13. CRYSTALLINE AGGREGATES

Large distinct crystals are comparatively rare among minerals. Most minerals consist of crystal aggregates which do not possess definite crystal faces. Such minerals are, however, crystalline, as may be determined by certain physical properties, particularly the optical properties. The kinds of crystalline aggregates are distinguished by certain terms which are constantly used in the description of minerals.

A mineral made up of plates is called **lamellar** (example, *barite*). If the layers are readily separated the term **micaceous** is used. An aggregate of more or less parallel imperfect crystals is called **columnar** (example, *aragonite*) and the same on a smaller scale is **fibrous** (example, *gypsum*). A flat columnar aggregate is said to be **bladed** (example, *cyanite*.) The term **granular** needs no explanation (example, *magnetite*).

The forms assumed by many aggregates derive their names from some natural object. **Nodular** is the term used for irregular rounded lumps (example, *pyrite*). **Mamillary** refers to low rounded prominences (example, *smithsonite*). **Botryoidal** is from a Greek word meaning a bunch of grapes (example, *chalcedony*). **Reniform** means kidney-shaped (example, *hematite*). **Pisolitic** is the term used for an aggregate of shot-like masses (example, *bauxite*), while **öolitic** is similar except in size, being like fish-roe (example, *calcite*). **Stalactitic** indicates that the mineral is found in icicle-like forms (example, *calcite*). **Dendritic** means branching like a tree (example, *copper*). **Concretions** are more or less spherical masses formed by the tendency of matter to gather around a center (example, *siderite*). A **geode** is a hollow concretion usually lined with crystals (example, *quartz*.) A **vug** is a cavity in a rock or vein lined with crystals.

Other terms such as mossy, wire-like, radiating, rosette-shaped, leafy, globular, etc., are self-explanatory.

Very few minerals are strictly amorphous. Chalcedony, though never occurring in distinct crystals, always shows a crystalline structure when examined between the crossed nicols of a polarizing microscope. Opal, on the other hand, is amorphous, for it remains dark between crossed nicols. Both cryptocrystalline minerals like chalcedony and amorphous minerals like opal often occur in botryoidal and mammillary forms.

#### **14. THE INTERNAL STRUCTURE OF CRYSTALS**

It is the general belief that matter is coarse-grained, being made up of discrete particles (or groups of particles) at small, but not infinitesimal, distances apart. Many physical phenomena such as expansion on heating, transmission of light, and the polarity of tourmaline can only be satisfactorily explained by means of this hypothesis.

In crystals it is only fair to assume that the particles have a regular arrangement, while in amorphous substances the arrangement is haphazard. The law of rational indices is one of the best proofs of some kind of molecular structure. A crystal is the outward expression of an internal structure. This internal structure is the essential character of a crystal. A fragment of quartz, though without crystal faces, may easily be distinguished from a fragment of glass by polarized light. A study of the physical properties (especially the optical properties) of crystals reveals the fact that the properties are the same for all parallel directions, but in general are different for directions not parallel.

From these and other considerations we are forced to the conclusion that the arrangement of molecules about any one molecule is the same as that about any other.

Haüy, the founder of crystallography, made the first contribution to the theory of crystal structure. A crystal of calcite,

accidentally dropped, broke into cleavage fragments. From this and other observations Haüy was led to suppose that crystals are made up of minute cleavage particles. By building up these particles any of the known forms of a mineral can be imitated. For example, in galena the cleavage particles are cubes. Omitting a certain number of these cubes various secondary faces would result. Thus in Figs. 242, 243, and 244 the dotted lines represent (110), (210), and (310) faces respectively. If the particles were very minute the faces would appear smooth. In this way Haüy discovered the law of rational indices.

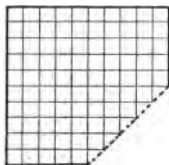


FIG. 242.

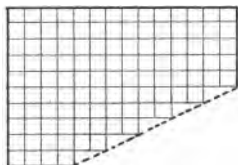


FIG. 243.

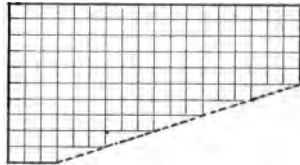


FIG. 244.

It is probable that the units of crystal structure are not in contact, also it is not necessary that they be cleavage particles, for some minerals have no cleavage. The centers of the molecules or their centers of influence, as they are probably in constant motion, may be represented by points. Then we need not assume any particular shape for the particles.

Bravais established the fact that only fourteen kinds of space-lattices or kinds of arrangement of the molecules are possible in crystals. They are as follows: cube (Fig. 245), centered cube (Fig. 246), cube with centered faces (Fig. 247), square prism (Fig. 248), centered square prism (Fig. 249), hexagonal prism (Fig. 250), rhombohedron (Fig. 251), rhombic prism (Fig. 252), centered rhombic prism (Fig. 253), rectangular prism (Fig. 254), centered rectangular prism (Fig. 255), clinorhombic prism (Fig. 256), monoclinic parallelepiped (Fig. 257), and triclinic prism or general parallelepiped (Fig. 258). In order to account for the thirty-two classes Bravais assumed that the molecules them-



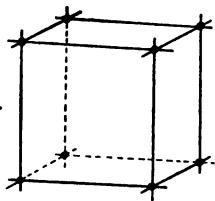


FIG. 245.

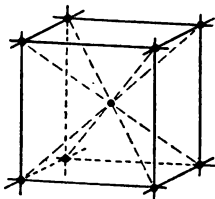


FIG. 246.

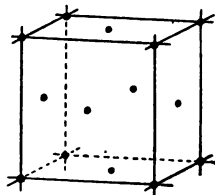


FIG. 247.

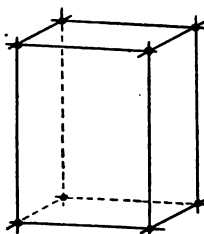


FIG. 248.

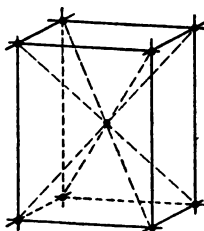


FIG. 249.

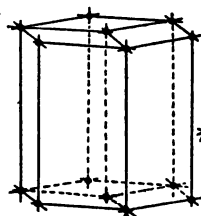


FIG. 250.

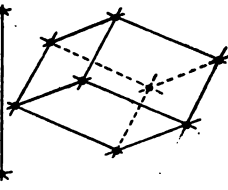


FIG. 251.

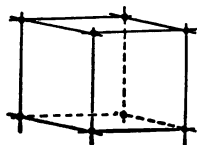


FIG. 252.

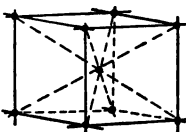


FIG. 253.

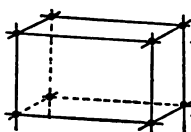


FIG. 254.

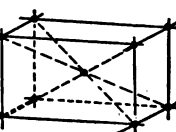


FIG. 255.

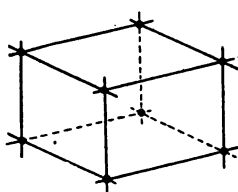


FIG. 256.

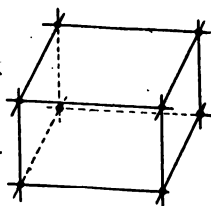


FIG. 257.

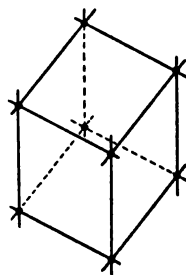


FIG. 258.

FIGS. 245-258.—The fourteen space-lattices of Bravais.

selves possess symmetry, but this is not necessary for even if they are without symmetry, their orientation in the unit cell of the space-lattice will account for all observed types of symmetry.

By considering infinite groups of movements, which include translations as well as symmetry operations, Fedorow, Schoenflies and Barlow have proved that two hundred and thirty types of crystal structure are possible.

There is an intimate connection between the axes of symmetry, regular arrangement of crystal molecules, and the rationality of indices. Only axes of 2-, 3-, 4-, and 6-fold symmetry have ever been found in crystals. Though this rests upon an empirical basis it would seem to be a law of nature for, of the thirty-two crystal classes deduced mathematically by assuming only these axes of symmetry, representatives have been found of all but one. Moreover, no crystal has ever been found which does not belong to one of these thirty-one crystal classes.

Following Lewis, it can be shown by a consideration of Figs. 259 and 260 that if we assume a system of particles arranged at small, finite distances apart we can prove that only axes of 2-, 3-, 4-, and 6-fold symmetry are possible. Let  $A_1, A_2$ , etc., represent centers of the particles and let  $A_1A_2$  be the smallest possible distance between any two of them.  $A_1$  and  $A_2$  also represent axes of symmetry. In Fig. 259 a revolution around  $A_1$  brings  $A_2$  to  $A_3$  and a revolution around  $A_2$  brings  $A_1$  to  $A_4$ . If the angle of revolution is  $60^\circ$ ,  $A_3 = A_4$  and  $A_1A_3 = A_2A_3 = A_1A_2$ . In this case we have an axis of 6-fold symmetry. If the angle of rotation is less than  $60^\circ$ ,  $A_1A_3$  is less than  $A_1A_2$ , which is contrary to hypothesis. Therefore no axis of symmetry of degree greater than six is possible. For an axis of 5-fold symmetry we have an angle of rotation of  $72^\circ$  ( $\frac{1}{5}$  of  $360^\circ$ ). Now a rotation of  $72^\circ$  around  $A_1$

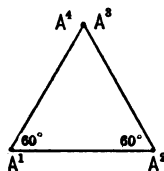


FIG. 259.

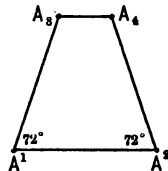


FIG. 260.

(Fig. 260) brings  $A_2$  to  $A_3$  and a rotation around  $A_2$  brings  $A_1$  to  $A_4$ . Then we have  $A_3A_4$  less than  $A_1A_2$ , which is contrary to hypothesis. Therefore only axes of 2-, 3-, 4-, and 6-fold symmetry are possible if crystals have a regular internal structure.

As only axes of 2-, 3-, 4-, and 6-fold symmetry have ever been found on crystals, in order to account for the observed facts we must assume a regular internal structure. A regular internal structure necessitates the rationality of the indices, for the various crystal faces are planes formed by the omission of a certain number of the particles in certain directions. It is often stated that the indices are simple whole numbers. This does not follow from the above argument nor does it fit the observed facts, for the indices of crystal faces are often large numbers. For example, on calcite crystals from Seguache County, Colorado, the author found as the dominant form a scalenohedron with the symbol  $\{49\cdot41\cdot90\cdot8\}$ . The faces were perfectly smooth and gave sharp images affording measurements which checked almost exactly with the calculated values. There are many such cases on record.

According to the structure theory of Bravais, the faces most apt to occur are those in which the centers of the particles are closest together. These are, of course, faces with simple indices such as  $\{110\}$ ,  $\{120\}$ ,  $\{130\}$ ,  $\{210\}$ ,  $\{310\}$ ,  $\{410\}$ , etc. But there is no reason why faces with large indices cannot occur, and in fact they do occur and are not to be explained as accidental. Out of 400 combinations of cerussite crystals Hubrecht mentions  $\{110\}$  as occurring 374 times;  $\{111\}$ , 370 times;  $\{010\}$ , 357 times;  $\{021\}$ , 279 times;  $\{011\}$ , 201 times;  $\{130\}$ , 192 times, while such forms as  $\{0\cdot13\cdot1\}$ ,  $\{14\cdot14\cdot1\}$ ,  $\{11\cdot13\cdot1\}$  and  $\{4\cdot86\cdot45\}$  occur only once or twice in the 400 combinations.

We cannot prove by direct measurement that the indices are rational for all measurements are subject to certain errors. That is, we cannot distinguish rational numbers from irrational numbers by any measurements we can make. But in an indirect way there is proof of the rationality of the indices as we have seen

above. The rationality of the indices and regular internal structure of crystals rest upon the empirical basis of the symmetry of crystals.

If we assume crystal structure it is easy to explain the relative abundance of crystal faces, the constancy of interfacial angles, varying crystal habit, and cleavage, as well as other physical properties. Fig. 261 represents in two dimensions the possible structure of an orthorhombic mineral. It is easy to account for

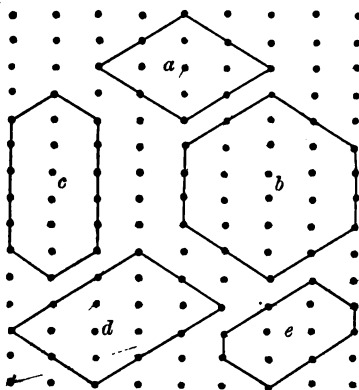


FIG. 261.

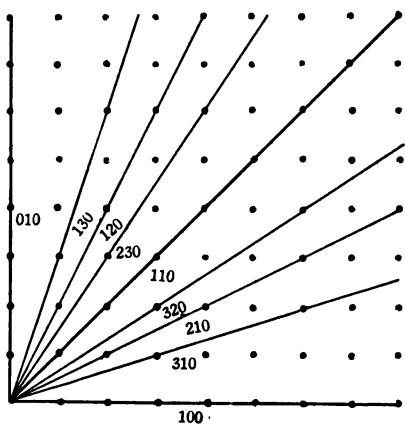


FIG. 262.

the rhombic habit *a*, the pseudo-hexagonal habit *b*, and the tabular habit *c*. Distorted crystals are represented by *d* and *e*. The angles between corresponding faces are necessarily identical.

Fig. 262 represents in plan the possible space-lattice of an isometric crystal. The faces most likely to occur are those in which centers of molecules are closest together. The probability of the occurrence of faces is, then, in the following order: (1) (100), (010); (2) (110); (3) (210), (120); (4) (310), (130); and (5) (320), (230). This agrees with the observed facts.

Figs. 263a and 263b represent respectively the plan and side elevation of an orthoclase crystal in outline. In the monoclinic

system there are two space-lattices possible, the clinorhombic prism and the monoclinic parallelepiped. As we shall see, the former suits orthoclase better. The small circles in the side elevation represent centers of molecules above and below the plane of the drawing. The drawings show why (010), (110), 130, (001),  $(\bar{1}01)$ , and  $(201)$  are the faces of common occurrence on

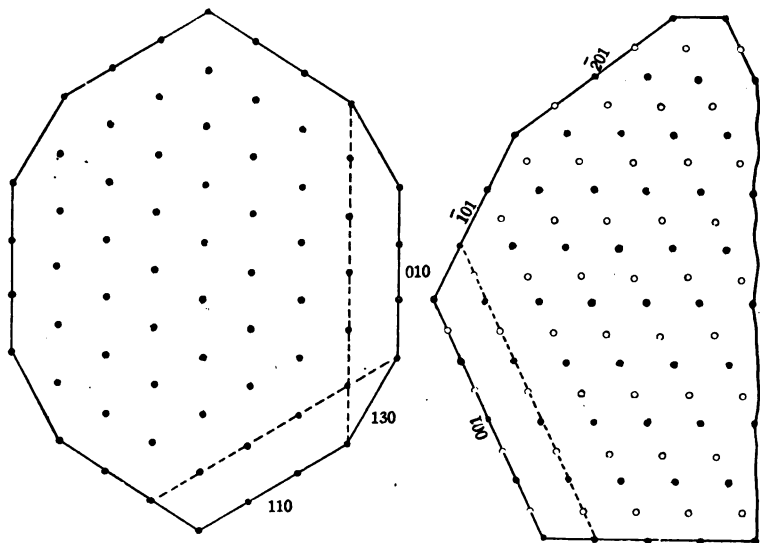


FIG. 263a.

FIG. 263b.

The probable structure of orthoclase.

orthoclase and why such faces as (120), (210), and (101) are of rare occurrence. According to Bravais cleavage is more prominent the greater the distance between adjacent rows of molecules. Thus in orthoclase we have cleavage parallel to (001), (010), and (110) as shown by the dotted lines.

## 15. THE GROWTH AND HABIT OF CRYSTALS

Crystals grow by accretion. They possess no organs as do plants and animals. Except for external faces a crystal is alike

in all its parts. They go through no growth stages, such as those observed in organisms. In the natural glass, obsidian, minute forms known as **crystallites** are very common. They consist of hair-like, fern-like, and feather-like forms as represented in Fig. 264. These are supposed to be incipient crystals and in some cases have been referred to the mineral augite. Crystallites have no action on polarized light. Larger forms (the swallow-tail forms of Fig. 264), which become dark and light with crossed nicols, are called **microlites**. In the case of sulfur crystallizing from carbon bisulfid solutions some observers have found that small spheres were formed first. These became arranged in rows like strings of beads and then united in acute forms and finally minute pyramidal crystals were the result (Fig. 397).

Crystals usually grow more rapidly in certain directions than in others. The general appearance of the crystal due to this difference of growth in different directions is called the **crystal habit**.

Such crystals as the micas usually have a limited growth in one direction and are flat. This is known as **tabular habit**. It may be described as thin tabular or thick tabular. In other cases the growth is largely in one direction, and we have the **prismatic habit**. In extreme cases we have **acicular** or needle-like crystals, or **capillary** crystals with the relative proportions of fine hairs. Other habits are defined as pyramidal, cubic, octahedral, etc.

The habit of crystals is probably partly inherent in the substance and partly due to external conditions such as temperature, pressure, and the presence of foreign substances. While little is known as to the cause of the habit of crystallized minerals,

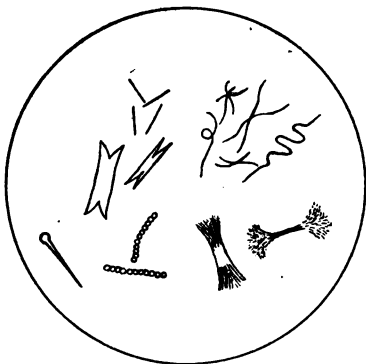


FIG. 264.—Crystallites and microlites.

some important experimental observations have been made in connection with this subject. For example, calcite may be obtained in small crystals from a solution of  $\text{CaCO}_3$  in carbonated water. Vater, a German investigator, found that if no foreign substance was present in the solution, the crystals were unit rhombohedra, but on the addition of sodium sulfate, calcium sulfate, etc., the habit of the crystals was changed. As more and more of these substances was added, the crystals became steeper rhombohedra and finally passed into prismatic crystals. Figs. 265, 266, and 267 illustrate the change in habit on adding sodium

sulfate. Alum, which usually crystallizes in octahedrons, separates from alkaline solutions in cubes.

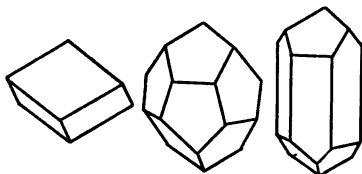


FIG. 265.

FIG. 266.

FIG. 267.

The habit of a mineral is often characteristic. Barite is usually tabular in habit. Crystals of barite prismatic in the direction

of the *c*-axis, when first found were described as a new mineral so unusual is this habit. Other minerals are marked by a great diversity of habits. The mineral calcite, for example, occurs in endless variety of combinations and the habit may be tabular, pyramidal, rhombohedral, scalenohedral, prismatic, as well as pseudo-cubic. (See Figs. 151 to 162, page 51.)

If the habit of a crystal changes during its growth this fact is often made apparent in transparent crystals by a so-called **phantom-crystal** which is different in color or marked by a row of inclusions. Fig. 268 represents a phantom crystal of barite from England. At an earlier stage the face (010) was present.

Striations on crystals may often be explained by the oscillatory combination of two forms. Thus while the prism of a quartz crystal is being formed there is a tendency all the while to form the rhombohedron, and this tendency is manifest in the striations. A magnified cross-section of a quartz crystal would appear as in Fig. 269.

Curved crystals may be the result of oscillatory combination of several forms or of small individual crystals in not quite parallel position.

Skeleton crystals are formed during the rapid growth of some crystals. Their formation may be illustrated by Fig. 270. Taking a rhombic crystal as a nucleus it will be seen that the amount of material available for a unit of surface is greater at the angles. Hence the crystals under certain conditions will grow more rapidly in these directions, finally producing the hollow forms known as skeleton crystals. The snow crystal of Fig. 439, page 309, is a skeleton crystal and not a twin crystal.

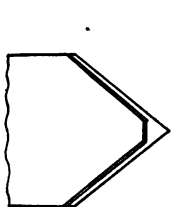


FIG. 268.



FIG. 269.

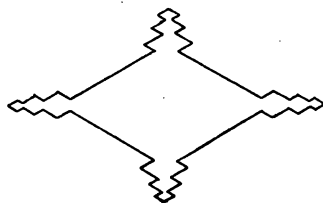


FIG. 270.

On some crystals there occur faces, with very high indices, the distribution of which agrees with the symmetry of the crystal. These are known as **vicinal faces** because they are *near* common faces with simple indices. The best example is the case of fluorite in which the cube faces, especially in twin crystals, are replaced by a very flat four-sided pyramid (Fig. 195). This is a tetrahexahedron with the indices  $\{32\cdot1\cdot0\}$ .

It often happens during the growth of a crystal, especially if rapid, that foreign minerals are included within the crystal. These inclusions may be irregularly arranged in various positions and for these the term *poikilitic* is used. In other cases there is a regular arrangement of inclusions as, for example, rutile



needles in phlogopite mica from Canada. Here the rutile needles are arranged in three directions at angles of about  $60^\circ$ , which are crystallographic directions of the mica (Fig. 271). This mica shows the phenomenon of **asterism**. When a hole in cardboard is viewed through a thin sheet of the mica held up to the light, a six-rayed star appears. Inclusions are sometimes arranged zonally in bands parallel to the outline of the crystal.

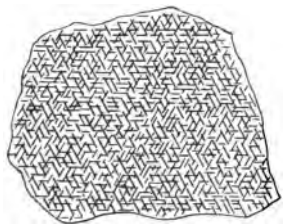


FIG. 271.

In case of rock-salt or halite the mother liquor often occupies a cubic cavity known as a **negative crystal** and frequently there is a bubble which changes position on moving the specimen. Quartz and topaz also sometimes show a moving bubble.

## 16. THE MEASUREMENT OF CRYSTALS

The starting point for all exact work in the description or determination of crystals is the measurement of their interfacial angles. It is the external or supplement angle that is used rather than the internal angle, the reasons being:

(1) the sum of the supplement angles of a zone is equal to  $360^\circ$ , (2) it is easier to estimate the supplement angle with the eye, and (3) the angle read off on the reflection goniometer is the supplement angle. Interfacial angles are measured

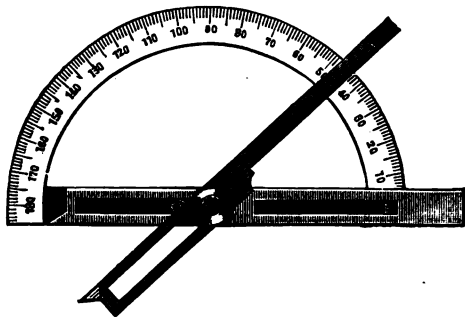


FIG. 272.—Contact goniometer (2/3 size).

either by a contact goniometer, which is a protractor made of cardboard or metal, or by an instrument called the reflection goniometer.

A very satisfactory contact goniometer is that devised by Penfield which consists of a graduated semi-circle printed on cardboard with a pivoted strip of celluloid (see Fig. 1, page 4). Fig. 272 is a metal goniometer made by Fuess of Berlin. With care fairly good results accurate to about  $\frac{1}{2}^\circ$  can be obtained with the contact goniometer, but the faces of the crystal must be smooth and of appreciable size.

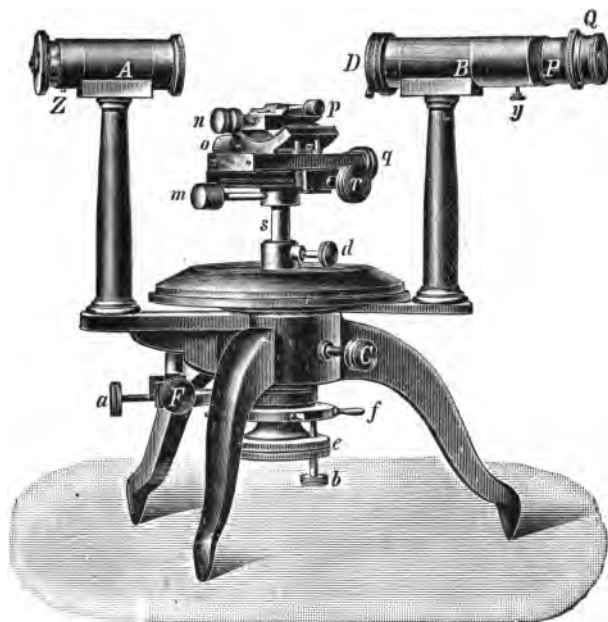


FIG. 273.—Reflection goniometer.

For more accurate work, especially on minute crystals, the reflection goniometer is used. The principle of measurement is as follows: If a bright face of a crystal is held close to the eye a reflection of a distant object such as a window bar can be obtained. On turning the crystal about, reflections are obtained from other faces. The angle through which the crystal is revolved to obtain the images from two adjoining faces is the supplement angle.

**The reflection goniometer**, the invention of Wollaston in 1809, originally consisted of a vertical graduated circle with a horizontal axis bearing the crystal carrier. In the modern type of goniometer the graduated circle is horizontal and the axis of revolution is vertical. Model IV, made by Fuess of Berlin, Fig. 273, is undoubtedly the best goniometer for student use. A central

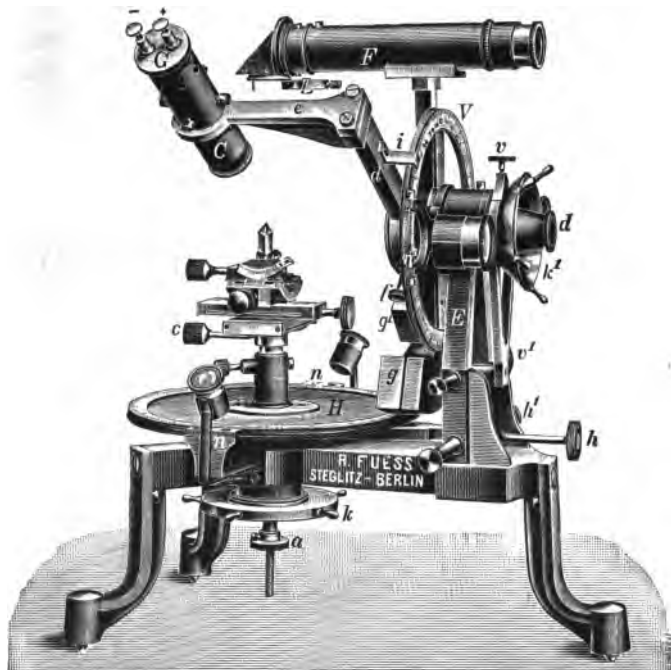


FIG. 274.—Two-circle goniometer (1/4 size.)

axis *s* bears a crystal carrier (axis of the graduated circle) with adjustments which are two sliding motions (*g* and *r*) at right angles and two tipping motions on circular arcs at right angles (*o* and *n*). A collimator *A* with a biconcave slit at the end and a telescope *B* which may be set at any angle to the collimator complete the equipment. A source of light, such as a Welsbach

burner, placed at the end of the collimator furnishes a beam of light which is reflected from the crystal, when in a certain position, into the telescope. Looking into the telescope one sees a biconcave-shaped image which may be bisected by the cross-wires in the telescope and then the reading on the vernier of the graduated circle is taken. The crystal carrier with the mounted crystal is revolved until an image is reflected from another face and so on for all faces of a zone. A separate set-up, which consists of making edges parallel to the axis of rotation by means of the adjustments on the crystal carrier, must be made for each zone.

Another type of goniometer is the two-circle or theodolite goniometer which consists of two graduated circles at right angles. Fig. 274 shows the two-circle goniometer of Czapski, made by Fuess of Berlin. Two angles corresponding to the longitude and to the co-latitude of a place on the earth's surface are obtained for each face. The advantage of the two-circle goniometer lies in the fact that only one set-up is required for all the faces on one-half of a crystal.

In the case of small crystals with dull faces the polarizing microscope with rotating stage may be used to advantage in measuring angles (see Fig. 333, page 124).

**A simple reflection goniometer**, may be made from the Penfield contact goniometer by fitting a wooden axis through the eyelet, the axis being provided with a wire pointer. Fig. 275 illustrates this device. By holding the goniometer, with the crystal mounted on the end of the axis with wax, so that the

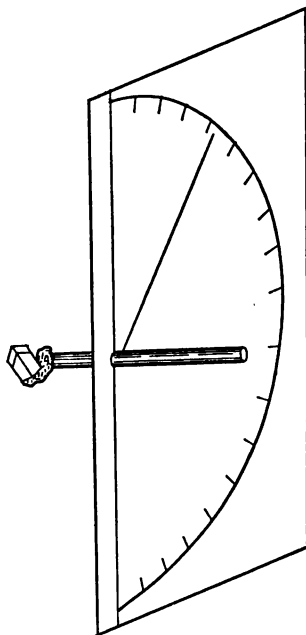


FIG. 275.—Simple reflection goniometer.

intersection edge of the faces is in line with the axis, an image of a distant object, such as a window-bar, on a crystal face is made to coincide with the edge of a table or similar line of reference. The reading of the pointer is taken. Then carefully getting the same image again, the goniometer is held firmly and the axis carrying the crystal is rotated until a similar image is obtained from an adjacent face. The supplement angle is the difference between the two readings. And so on for other faces of the zone. As the protractor includes but  $180^\circ$ , only part of the zone can be measured at one time.

## 17. THE STEREOGRAPHIC AND OTHER PROJECTIONS OF CRYSTALS

In order to study the symmetry and the angular relations of crystals use is often made of a projection of a crystal. By representing each face by a point, their shape and size are eliminated and the symmetry made apparent.

There are various methods of projection, but the principal one used in crystallography is the **stereographic projection**. Imagine a crystal within a sphere, their centers coinciding. Radii are drawn normal to the faces of the crystal, intersecting the sphere in points. Each face then is replaced by a point called the **pole of the face** (Fig. 276). As it is difficult to make measurements on a spherical surface, a projection of the poles is made on a plane.

The plane of projection is a plane through the center of the sphere. The projection of any face on this plane is the intersection of a line drawn from the south pole of the sphere to the pole of the face with this plane. In Fig. 276 the dots are poles of the faces and their projections are the small crosses.

The most important property of the stereographic projection is that all circles on the sphere are projected as circles or as straight lines. All vertical great circles appear as diameters of the primitive circle, as the projection of the horizontal great

circle is called. All oblique great circles appear as arcs of great circles passing through the extremities of diameters. All faces of a zone appear on the arc of a great circle.

The method of projecting poles depends upon their position. Poles on the horizontal great circle are laid off directly on the

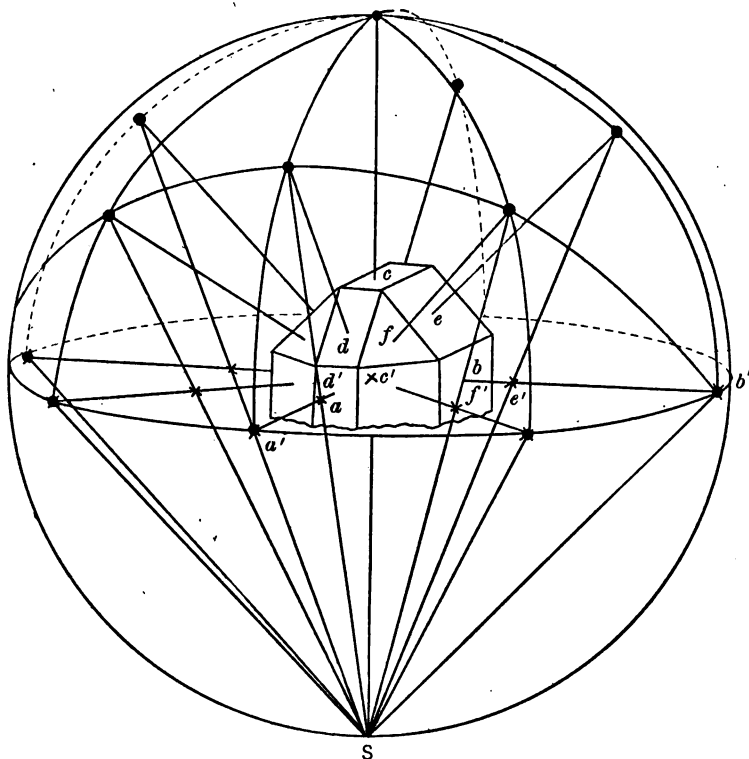


FIG. 276.—Illustrating the stereographic projection.

primitive circle. Poles on vertical great circles are projected by first laying off angles on the primitive. Lines are then drawn from these points to the south pole on the opposite side (Fig. 277). The projections are the intersections of these lines with

the trace of the vertical great circle. The poles on an oblique great circle are projected by first finding what is called the **pole of the great circle**. This is a point on the diameter normal to the great circle and  $90^\circ$  from its intersection with the great circle. This pole is found as indicated in Fig. 278, *p* being the pole. Angles on oblique great circles are laid off on the primitive. The intersection of lines drawn from these points to the pole of the great circle with the great circle itself is the required projection (Fig. 279).

A great circle may be drawn when three points are known. The center of the circle is the intersection of the perpendicular bisectors of the chords of any two arcs of the great circle. A great circle of long radius may be drawn by a beam compass or by a piece of thin flexible steel bent so as to fit the known points.

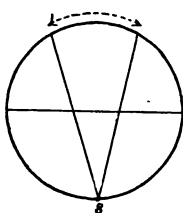


FIG. 277.

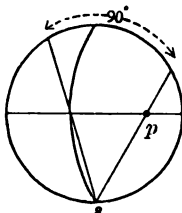


FIG. 278.

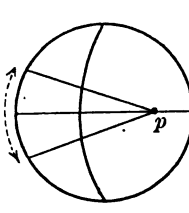


FIG. 279.

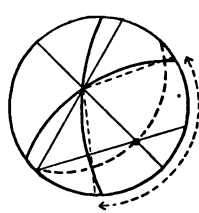


FIG. 280.

An important property of the stereographic projection is that the angles between great circles are projected in their true value. To determine the angle between two great circles draw the great circle (dotted arc of Fig. 280) of which their intersection is the pole. The angle between the two great circles is the same as the interfacial angle on this great circle. This may be determined by the method illustrated in Fig. 279, for the intersection of the two great circles corresponds to the point *p*.

The work of plotting and measuring the angles of a stereographic projection has been much simplified by Penfield. He used large sheets with a graduated circle of 7 cm. radius on which are printed several scales, one for laying off stereographic

degrees on a diameter, another for giving radii of various great circles, and another for giving radii of small vertical circles. Besides these sheets he devised several protractors printed on transparent celluloid to fit a circle of 7 cm. radius. One is a great circle protractor giving arcs of great circles for every other degree. This may be pivoted at the center and swung around to

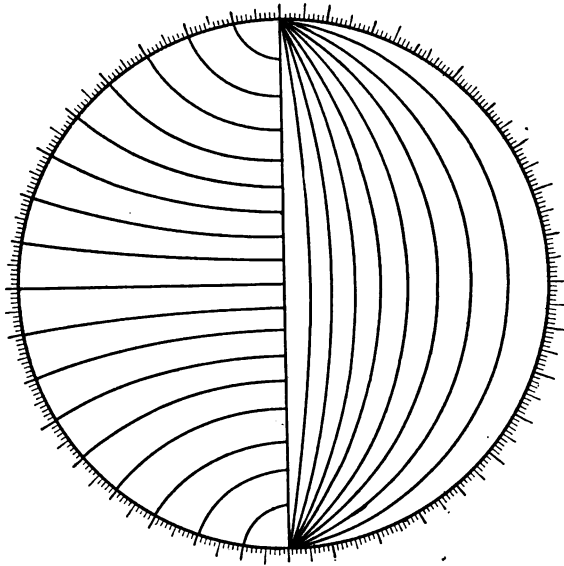


FIG. 281.—Penfield's stereographic protractors.

pick out all the faces of a zone. Another protractor is of small vertical circles. This laid down on a projection will give the angular distance between any two points on the arc of a great circle. The right half of Fig. 281 shows the great circles for every ten degrees and the left half, the small vertical circles for every ten degrees.

The stereographic projection affords a ready means of solving a



spherical triangle graphically. For example, in Fig. 282 given the angle  $A$  and the sides  $b$  and  $c$  of a spherical triangle, to find the angles  $B$  and  $C$  and the side  $a$ . From any point  $A$ , the side  $b$  is laid off on the primitive, then a great circle is drawn making the angle  $A$  with the primitive by laying off the stereographic degrees on the diameter  $90^\circ$  from  $A$ . The side  $c$  is laid off on this great

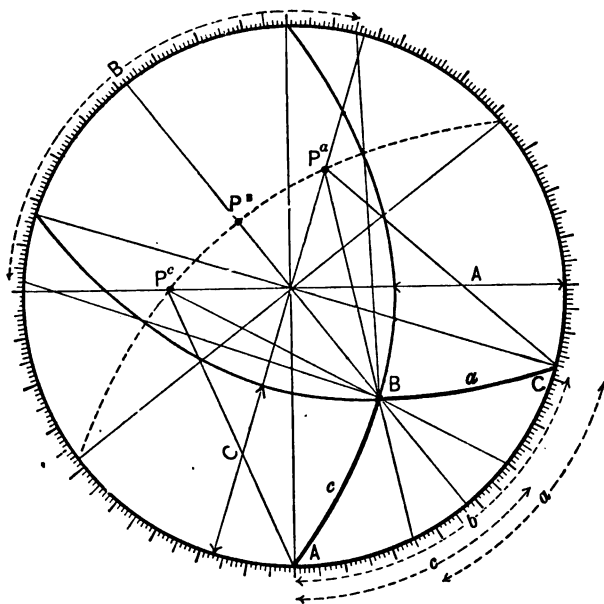


FIG. 282.—Graphic solution of a spherical triangle.

circle and this determines the point  $B$ . A great circle  $BC$  is drawn. The angle  $C$  is measured on a diameter drawn  $90^\circ$  to  $C$  and the angle  $B$  on a great circle of which  $B$  is the pole. The work is very easy if the Penfield sheets and protractors are used. In the example: given  $A = 49^\circ$ ,  $b = 73^\circ$ ,  $c = 50^\circ$ ; found graphically  $a = 48^\circ$ ,  $B = 103^\circ$ ,  $C = 51^\circ$ .

Another method of projection is the **gnomonic projection** in which the plane of projection is a plane perpendicular to the *c*-axis of the crystal and at a unit's distance from the center. This plane is parallel to the 001 face in all except the monoclinic and triclinic systems. From the center of the crystal lines are drawn normal to the crystal faces and extended to cut the plane of projection. The principal advantages of the gnomonic projection are: (1) that zones are represented by straight lines and (2) that the Miller indices may be obtained directly from the

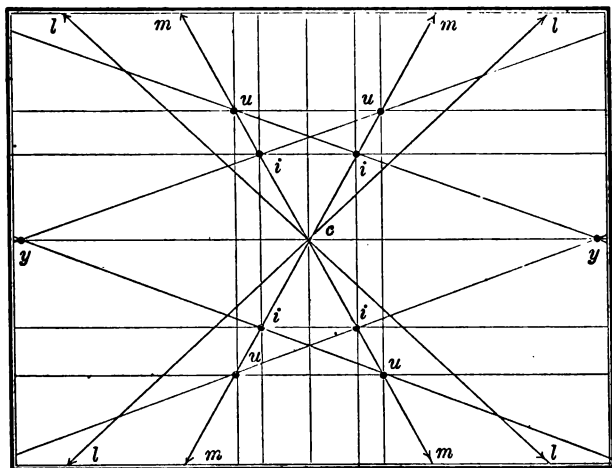


FIG. 283.—Gnomonic projection.

projection. Fig. 283 is a gnomonic projection of the topaz crystal represented in Fig. 77. The circle has a radius of  $45^\circ$  (gnomonic degrees). The prism faces *m* and *l* are represented at the edge of the drawing by arrows as they are projected at infinity.

The **linear projection** which is used in connection with crystal drawing, is made up of intersecting lines which represent faces. The lines are the intersections of faces, shifted parallel to themselves so that they cut the vertical axis, *c*, at

any face ( $pqr$ ) that belongs to the zone  $[uvw]$  the following must be true  $up + vq + wr = 0$ . This is known as the **equation of zone control**. If two indices of a face in a known zone are given, we may then find the third index in this way. If a face ( $hkl$ ) is common to two zones  $[uvw]$  and  $[u'v'w']$  the following relation is true:  $h = vv' - v'v$ ;  $k = uw' - u'w$ ;  $l = uv' - u'v$ . In all of these careful attention must be given to signs.

The method of determinants may be used to ascertain whether any three given faces are in a zone or not. The indices are written in the form:

$$\begin{array}{c} h_1 \ k_1 \ l_1 \\ h_2 \ k_2 \ l_2 \\ h_3 \ k_3 \ l_3 \end{array}$$

The sum of the left to right products  $(h_1 \times k_2 \times l_3) + (k_1 \times l_2 \times h_3) + (l_1 \times h_2 \times k_3)$  must equal the sum of the right to left products  $(l_1 \times k_2 \times h_3) + (k_1 \times h_2 \times l_3) + (h_1 \times l_2 \times k_3)$  if the three faces are in a zone. This fact may usually be told by inspection if the three faces are written in the determinant form as above.

A graphic method of obtaining the Miller indices of an orthorhombic crystal is indicated in Fig. 286, which represents the cerussite crystal sketched in the lower corner of the drawing. The known faces<sup>1</sup> are  $a\{100\}$ ,  $m\{110\}$ ,  $b\{010\}$ , and  $k\{011\}$ . The problem is to determine the indices of the faces  $r$ ,  $x$ ,  $i$ ,  $y$ , and  $p$ . Let us suppose that measurements have been made in the following zones:  $[amrb]$ ,  $[xkib]$ ,  $[apk]$ , and  $[ay]$ . A stereographic projection is first made from the measurements of the interfacial angles with  $[amrb]$  on the primitive circle. The other faces are projected as indicated on page 83.

First take the zone of  $hk0$ 's. A prolonged radius is drawn through  $m(110)$ . From the intersection of a tangent at  $a$  with this radius a line  $RT$  perpendicular to  $Ob$  is drawn. This constitutes the **unit scale line**. Intercepts of the radii of  $hk0$  and  $hkl$  faces on this line are in the ratio of  $h:k$  in terms of the radius

<sup>1</sup> Unit faces must be known or assumed.

involved. The graphic method is based upon a stereographic projection.

The determination of the indices is much simplified by making use of zonal relations. Faces of crystals very commonly occur in several prominent zones. By inspection, the parallelism of edges is the test of a zone. A more accurate method is to test the reflections of various faces in the reflection goniometer. The **indices of a zone** are three numbers obtained in the following

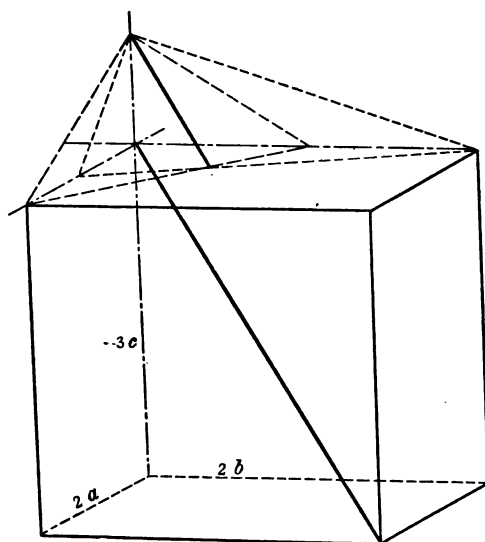


FIG. 285.—To explain meaning of a zone symbol.

manner from any two faces of the zone,  $(hkl)$  and  $(h'k'l')$ .  $(kl'-lk')$ ,  $(lh'-h'l')$ ,  $(hk'-kh')$ . These three values, usually written  $[uvw]$  in brackets to distinguish them from face or form indices, are the coördinates of a point which determines a parallelepiped such that its diagonal from the origin to the point mentioned is parallel to the intersection edge of the two faces (Fig. 285). In the figure the faces are  $(122)$  and  $(212)$ ; the indices of the zone,  $[223]$ . For

one ( $h0l$ ) face the position of  $Q$ , a possible unit face, must be determined. This is on the great circle through  $b$  and  $p$ .

To determine the indices of the  $hkl$  faces use is made of zonal relations. For zones through (100) the ratio  $k:l$  is constant for all faces and similarly for zones through (010) the ratio  $h:l$  is constant and for zones through (001) the ratio  $h:k$  is constant. So that for all  $hkl$  faces the corresponding  $Ok l$ ,  $h0l$  or  $hk0$  faces are found by constructing the appropriate arcs of great circles.

In the figure the zone circles  $akp$ ,  $bpQ$ , and  $Op m$  (a straight line) are drawn. So that the symbol for  $p$  is (111) as it satisfies both  $k:l=1:1$  and  $h:k=1:1$ . The zone circle through  $b$  and  $p$  determines  $Q$ , the pole of a possible face (101).

To determine the symbol of  $y$  the zone  $aO$  is folded over to  $aU$ , the pole  $y$  and the pole of a possible face  $Q$  taking the positions  $y'$  and  $Q'$ . Radii through  $y'$  and  $Q'$  are drawn and another unit scale line  $VW$  is established. As the distance  $VW' = \frac{1}{2} VW$  the symbol of  $y$  is (102).

Fig. 287 is a diagram<sup>1</sup> used to determine the symbol of faces in a given rectangular zone if the symbol of one of them is known. Its construction is simple. In a square of convenient size radii are drawn from one corner for every other degree. From the top line perpendiculars are dropped for each of the radii. Horizontal lines divide the sides of the square into fractional parts corresponding to the more common indices, namely: 1:6, 1:5, 1:4, 1:3, 2:5, 1:2, 3:5, 2:3, 3:4, 4:5, and 5:6.

The method of using the diagram may be illustrated by an example. In cerussite the angle (001:011) is  $35^{\circ} 52'$ . Along the radius for  $36^{\circ}$ , the horizontal line reading 1:2 (on the left) cuts the vertical line for  $20^{\circ}$ . The calculated angle for (001:012) is  $19^{\circ} 52\frac{1}{2}'$ . The angle for (001:021) is found at the intersection of this same horizontal line (it reads 2:1 on the right) with the vertical for  $36^{\circ}$ . This intersection is on the diagonal for  $55^{\circ} 30'$ .

<sup>1</sup> G. H. F. Smith describes a similar device called the moriogram. *Mineralogical Magazine*, Vol. 14, p. 49, 1904.

(calculated  $55^{\circ} 20'$ ). The value of the  $c$ -axis is given at the bottom of the vertical through  $36^{\circ}$  as 0.725 (calculated 0.723).

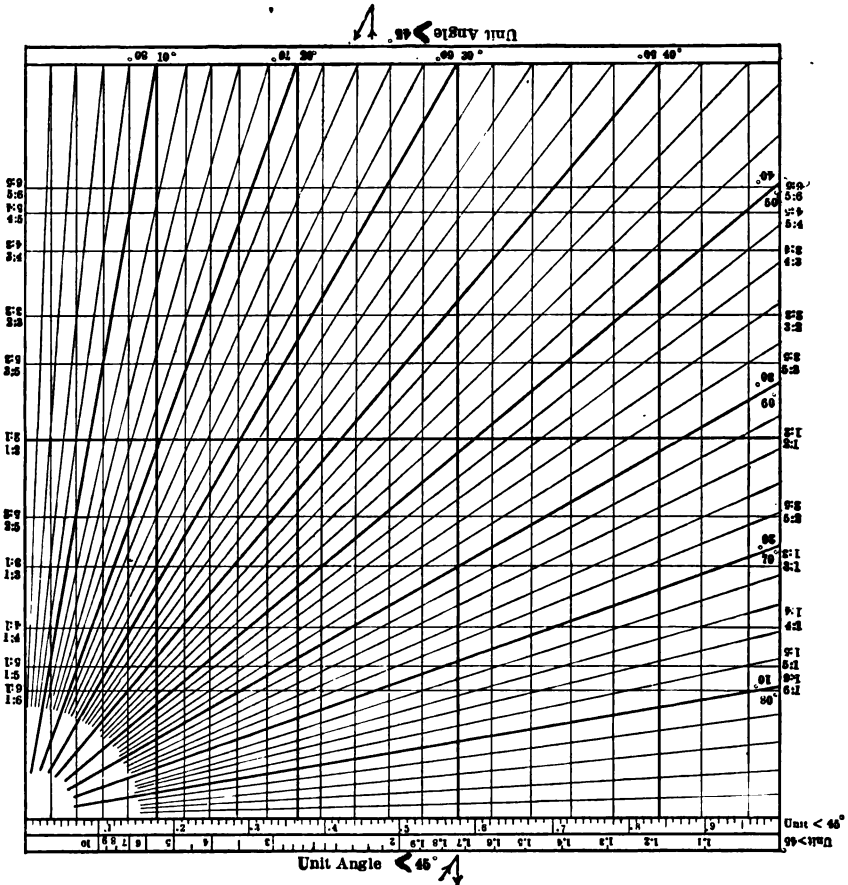


FIG. 287.—Diagram for determining indices of crystal faces.

In the preceding example the unit angle was less than  $45^{\circ}$ . If the unit angle is greater than  $45^{\circ}$  the diagram is turned upside down. The readings for angles less than the unit are made on the

verticals, the indices being found on the left while the readings for angles greater than the unit are given on the radii with the indices on the right. For example, in barite  $(001:011) = 52^\circ 43'$ ,  $(001:012)$  as found  $= 33^\circ 15'$  (calc.  $33^\circ 18'$ ) and  $(001:021)$  as found  $= 69^\circ$  (calc.  $69^\circ 9\frac{1}{2}'$ ). In this case  $c$  from the scale at the bottom (now the top) is about 1.32 (calc. 1.313).

For establishing the axial elements, which consist in the most general case of the axial ratios  $a:b:c$  and the axial angles  $\alpha$ ,  $\beta$ , and  $\gamma$ , it is necessary either to take the measurement of selected faces (usually unit faces) and use these for the calculation or to combine the measurements of all the faces, weighting those from the best signals. The formulæ used in the simpler cases are given below.

After the axial elements have been established, these values and the graphically determined indices for the various faces are substituted in the formulæ and the theoretical angles obtained become part of the record for the mineral. The same formulæ may be used throughout. Thus the formula  $a = \frac{h}{k} \tan (100:hk0)$  may be solved for the axis  $a$ , for the angle  $(100:hk0)$  and even for the ratio  $h:k$ , though a graphic determination of the indices is preferable to calculation.

#### *Formulæ used in Simple Cases*

##### **Orthorhombic System :**

$$a = \tan(100:110) = \frac{h}{k} \tan(100:hk0)$$

$$a = \cot(010:110) = \frac{h}{k} \tan(010:hk0)$$

From Fig. 288 it may be seen that  $\frac{1}{2}(hk0:\bar{h}k0) = (100:hk0)$  and  $\frac{1}{2}(hk0:\bar{h}k0) = (010:hk0)$ .

$$c = \tan(001:011) = \frac{l}{k} \tan(001:0kl)$$

$$c = \cot(010:011) = \frac{l}{k} \cot(010:0kl)$$

From Fig. 289,  $\frac{1}{2}(0kl:0\bar{k}l) = (001:0kl)$  and  $\frac{1}{2}(0kl:0k\bar{l}) = (010:0kl)$ .

$$\frac{c}{a} = \tan(001:101) = \frac{l}{h} \tan(001:hOl)$$

$$\frac{c}{a} = \cot(010:101) = \frac{l}{h} \cot(010:hOl)$$

From Fig. 290,  $\frac{1}{2}(hOl:h\bar{O}l) = (001:hOl)$  and  $\frac{1}{2}(hOl:hO\bar{l}) = (010:hOl)$ .

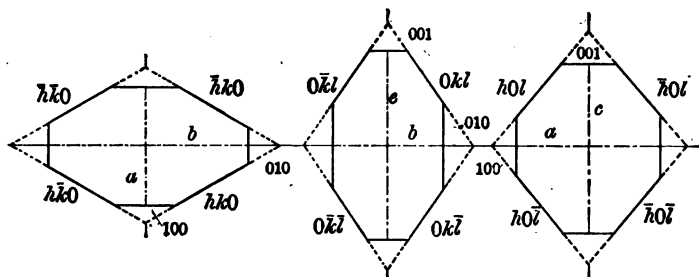


FIG. 288.

FIG. 289.

FIG. 290.

### Monoclinic System :

$$\beta = 100 \wedge 001$$

$$a = \frac{\cot(010:110)}{\sin \beta} = \frac{h}{k} \frac{\cot(010:hk0)}{\sin \beta}$$

$$a = \frac{\tan(100:110)}{\sin \beta} = \frac{h}{k} \frac{\tan(100:hk0)}{\sin \beta}$$

$$c = \frac{\tan(001:011)}{\sin \beta} = \frac{l}{k} \frac{\tan(001:0kl)}{\sin \beta}$$

$$c = \frac{\cot(010:011)}{\sin \beta} = \frac{l}{k} \frac{\cot(010:0kl)}{\sin \beta}$$

$$\frac{c}{a} = \frac{\sin(001:101)}{\sin(100:101)} = \frac{l}{h} \frac{\tan(001:hOl)}{\sin(100:hOl)}$$

**Triclinic System.** The mathematical relations are very complex here. Five independent angles are necessary to establish the five axial elements  $a$ ,  $c$ ,  $\alpha$ ,  $\beta$ , and  $\gamma$  ( $b=1$ ).



**Tetragonal System :**

$$c = \tan(001:011) = \frac{l}{k} \tan(001:0kl)$$

$$c = \cot(010:011) = \frac{l}{k} \cot(010:0kl)$$

$$c = \sqrt{2} \tan(001:111) = \frac{l}{h} \sqrt{2} \tan(001:hhl)$$

$$c = \sqrt{2} \cot(110:111) = \frac{l}{h} \sqrt{2} \cot(110:hhl)$$

The angles in the prism zone are constant for all tetragonal crystals. Some of the prominent angles are:

$$(100:110) = 45^\circ 0'$$

$$(100:430) = 36 \quad 52$$

$$(100:320) = 33 \quad 41$$

$$(100:210) = 26 \quad 34$$

$$(100:310) = 18 \quad 26$$

**Hexagonal System :**

$$c = \cos 30^\circ \tan(0001:10\bar{1}1) = \frac{l}{2h} \cos 30^\circ \tan(0001:h0\bar{h}l)$$

$$c = \tan(0001:11\bar{2}2) = \frac{l}{2h} \tan(0001:h \cdot h \cdot 2\bar{h} \cdot l)$$

The angles in the prism zone are constant for all hexagonal crystals. The prominent angles are:

$$(10\bar{1}0:11\bar{2}0) = 30^\circ 0'$$

$$(10\bar{1}0:21\bar{3}0) = 19 \quad 6\frac{1}{2}$$

$$(10\bar{1}0:31\bar{4}0) = 13 \quad 54.$$

**Isometric System.** There are no axial elements to be determined. All isometric crystals have the same angles for corresponding forms. The more prominent angles are:

$$(100:111) = 54^\circ 44'; (100:110) = 45^\circ 0'; (111:110) = 35^\circ 16';$$

$$(110:101) = 60^\circ 0'; (111:1\bar{1}1) = 70^\circ 32'; (210:100) = 26^\circ 34';$$

$$(211:121) = 48^\circ 11\frac{1}{2}'.$$

For other isometric angles see Dana, *System of Mineralogy*, 6th edition, pp. xx-xxvi.

## 19. THE REPRESENTATION OF CRYSTALS

Representations of crystals may be made by means of models or drawings. On account of their size and ideal symmetry crystal models are extensively used in the elementary study of crystallography. Although seemingly more perfect than crystals, yet in reality they are crude in comparison. The angles are never as exact as in crystals and they fail to give the clue to symmetry by differences in luster, striations, and other markings on various

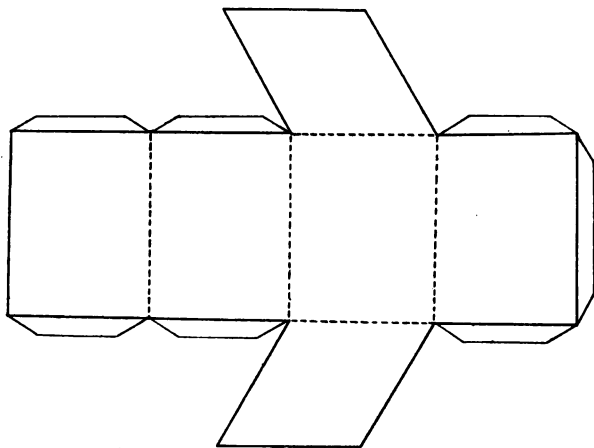


FIG. 291.—Crystal net.

faces that crystals do. Crystal models are made of wood, glass, pasteboard, or plaster of Paris. Those most used are the models made from pear-tree wood by German dealers.

A drawing like Fig. 291, which cut out and pasted together, forms a hollow pasteboard model is called a **crystal net**. The student will find it very instructive to make crystal nets for the simple crystals of various systems. These can be filled with plaster of Paris and the paper removed when the plaster has solidified.

The principal purpose of a crystal drawing is to give an idea of the crystal habit. While the various forms are represented in their relative size and shape the drawing represents, as a rule, a crystal in ideal symmetry free from distortion. The reason for this is that the ideal drawing stands for crystals with all possible distortions. In some cases where the crystal has a peculiar habit or where a single crystal is at hand, the faces may be shown in their actual development. Fig. 292 illustrates a topaz crystal drawn in this way.

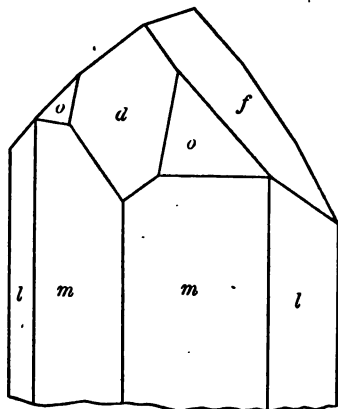


FIG. 292.—Clinographic drawing.

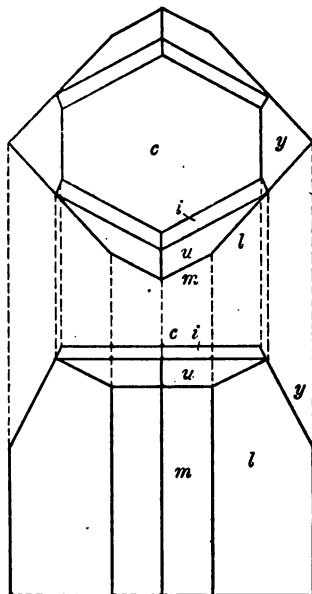


FIG. 293.—Orthographic drawing.

There are two kinds of crystal drawings; the **orthographic** in which the projectors are normal to the plane of projection which is usually a horizontal plane, and the **clinographic** in which the projectors are inclined to a plane of projection which is usually a vertical plane.

An orthographic drawing is made by dropping perpendiculars from the vertices to the plane of projection. All faces perpendicular to the plane of the drawing appear as lines inclined to



$OB$  and  $OC$  is  $93^\circ 8'$ , the proportional lengths of the axes being  $OA:OB:OC=37:100:104$ . This is equivalent to a rotation of  $18^\circ 26'$  to the left and to a tipping forward of  $9^\circ 28'$ .

This axial cross is modified for other systems. For example, the axial cross for an orthorhombic crystal with the axial ratio  $0.8:1:1.3$  is  $0.8 \times 37:100:1.3 \times 104$ . In the hexagonal system there is a third lateral axis. In Fig. 295 make  $OS$  equal to  $1.732 \times OA$ . Join  $S$  with  $B$  and  $B'$ . Bisect  $BS$  and  $BS'$  at the points  $R$  and  $Q$ .  $ROR'$ ,  $QOQ'$ , and  $BOB'$  are the three lateral axes. In the monoclinic and triclinic systems the angles between the

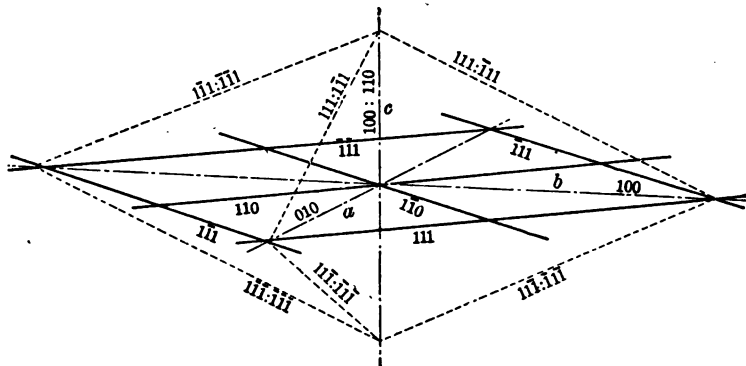


FIG. 297.—Showing method of clinographic drawing.

axes are also modified. For the angle  $\beta$  between  $a$  and  $c$  the position of the  $a$ -axis is changed as follows: On the axis  $OC$  (Fig. 296) the distance  $OM = \cos\beta \times OC$  is laid off and on the axis  $OA$  the distance  $ON = \sin\beta \times OA$  is laid off. Then the  $b$ -axis is the line  $QOQ'$ ,  $QO$  being the diagonal of a parallelogram  $MQNO$ . The lengths of the axes are modified as in the other systems. After the axes are projected in their proper positions the next step is to plot a linear projection of the crystal on these axes by taking the reciprocal of the Miller indices and then making the third term equal to unity. The desired direction of the intersection edge of the two faces is a line joining the intersection of the linear



projection of the two faces with the extremity of the vertical axis. Fig. 297 shows the method of construction of the clinographic drawing of the wernerite crystal of Fig. 299. The dot-and-dash lines are the axes of reference; the heavy lines, the linear projection constructed on the axial cross; while the dotted lines are the directions of the intersection edges. The direction intersection of faces like (111) and (110), which do not intersect, is simply the direction of the lines.

In Fig. 298, representing the construction of the wernerite crystal of Fig. 299, use is made of a stereographic projection. The plane of projection is an oblique plane in which the angle of rotation is  $18^{\circ} 26'$  ( $\tan^{-1} \frac{1}{2}$ ) and the tipping angle,  $9^{\circ} 28'$  ( $\tan^{-1} \frac{1}{3}$ ). These angles determine the point  $m$ . A great circle  $SmS'$  is drawn.  $N$  is the pole of this arc,  $mN$  equaling  $90^{\circ}$  (stereographic degrees). The intersection of a zone with the faces (111) and ( $\bar{1}\bar{1}1$ ) with this great circle is the point  $r$ . A line is drawn from  $N$  through  $r$  intersecting the primitive circle at  $t$ . A line perpendicular to the radius through  $t$  is the desired intersection edge of the two faces (111) and ( $\bar{1}\bar{1}1$ ) and all other faces of the zone. The advantage of this method is that nothing need be known of the indices or axial elements.

## PART II

### THE PHYSICAL PROPERTIES OF MINERALS

The crystal form is an outward expression of an internal molecular structure, and even when the external form is wanting the crystalline nature may usually be determined by some physical property. Some of the physical properties such as specific gravity are independent of the direction and are called **scalar** properties, while others such as cohesion and effect of light, heat, and electricity can be represented by a line of given length and direction, hence the term **vectorial** properties. A crystal may be defined as a homogeneous solid body the properties of which are the same in parallel directions, but in general are different in non-parallel directions.

In this part of the book the simpler physical properties such as cleavage, hardness, and specific gravity are considered, while the optical properties are left for another part. The thermal and electrical properties of minerals are of very little practical importance, and are therefore omitted.

#### 1. Cleavage

Many crystals have the property of breaking with smooth surfaces in certain directions which are parallel either to crystal faces or to possible crystal faces. This important property is called **cleavage**. Galena, which usually crystallizes in cubes, has a cubic cleavage (Fig. 300) while fluorite, also crystallizing in cubes, has an octahedral cleavage (Fig. 301), but the octahedron is a form sometimes found on fluorite. Cleavage is defined according to the direction as cubic, rhombohedral, prismatic, etc., and according to the character of the surface, such terms as imperfect,



good, perfect, and very perfect being used. Thus the micas have a very perfect cleavage parallel to (001) (Fig. 302), while the feldspars have a perfect cleavage parallel to (001) and good cleavage parallel to (010) (Fig. 303).

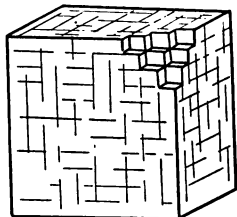


FIG. 300.—Cubic cleavage.

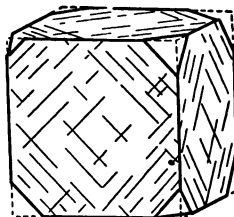


FIG. 301.—Octahedral cleavage.

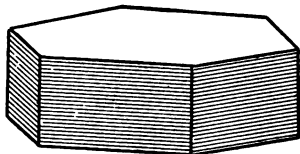


FIG. 302.—Mica cleavage.

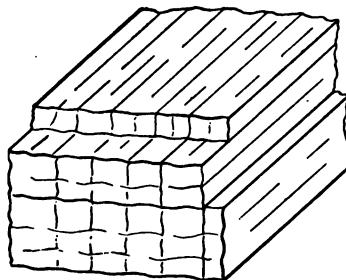


FIG. 303.—Feldspar cleavage.

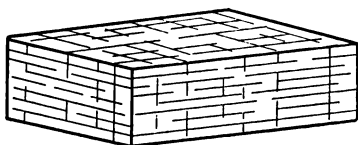


FIG. 304.—Barite cleavage.

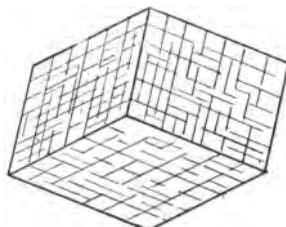


FIG. 305.—Calcite cleavage.

Cleavage conforms to the symmetry of the crystal. In barite, an orthorhombic mineral, the cleavage is perfect in one direction parallel to (001), and less perfect in two directions parallel to (110)

(Fig. 304). In gypsum there is a very perfect cleavage parallel to (010), an imperfect cleavage with conchoidal surface parallel to (100) and an imperfect cleavage with fibrous surface parallel to ( $\bar{1}11$ ). The relation of a cleavage fragment to a crystal is shown in Fig. 306, the inner rhombic figure being the result of cleavage. A line normal to the paper is an axis of two-fold symmetry for the cleavage fragment as well as for the crystal. In fluorite the octahedral cleavage conforms to the symmetry of the hexoctahedral class of the isometric system. In calcite, whatever the shape of the crystal, the cleavage is perfect rhombohedral in three directions at angles of  $74^{\circ} 55'$  to each other. Fig. 305 represents a cleavage of calcite with three surfaces and intersecting cleavage traces on each.

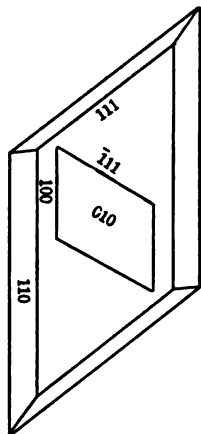


FIG. 306.—Relation of cleavage to crystal (gypsum).

Cleavage is a fairly constant property of minerals and is invaluable in the rapid recognition of minerals. Such minerals as calcite, fluorite, feldspars, amphiboles, and gypsum are distinguished principally by their cleavage.

On the other hand, such minerals as quartz and garnet, possess no cleavage. They break with an irregular **fracture**. In chalcedony the fracture is conchoidal (curved like the interior of a shell). Other terms applied to fracture are splintery, hackly, even, and uneven which are self-explanatory.

A table giving cleavage directions of important minerals will be found on pages 219-222.

## 2. Parting

This term is applied to the separation due to some molecular disturbance such as twinning. Cleavage may be obtained in any part of a crystal in the given direction, the size and the number of the cleavage particles being limited only by mechanical appli-

ances. **Parting**, on the other hand, only takes place in certain definite planes, those of the molecular disturbance. In a cubic cleavage of rock-salt, if pressure is applied in a direction normal to a vertical diagonal plane, a surface normal to the direction of pressure is developed, the shaded plane in Fig. 307. In this case we have an example of dodecahedral parting. If pressure is applied by a dull knife edge normal to the obtuse edge of a cleavage rhombohedron of calcite a small portion of the calcite will be reversed in position, forming a twin with  $(01\bar{1}2)$  as twinning

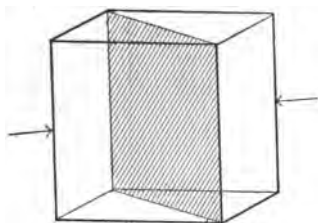


FIG. 307.—Halite parting.

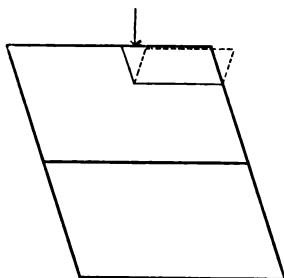


FIG. 308.—Calcite parting.

plane. This small portion of calcite may be easily removed, the parting being parallel to  $(01\bar{1}2)$  and produced in this case by twinning. This is illustrated in Fig. 308.

Prominent examples of parting are the following: basal parting  $(001)$  in diopside (Fig. 94, page 35), basal parting  $(001)$  in stibnite, octahedral parting  $(111)$  in magnetite, and rhombohedral parting  $(01\bar{1}2)$  in calcite.

### 3. Tenacity

The terms brittle, tough, and malleable are used in describing minerals. A malleable substance is one that can be cut by a knife and also flattened out with a hammer. Gold is so malleable a substance that it may be beaten into sheets about one-three hundred thousandth of an inch thick. A **sectile** substance is one that can be

cut by a knife, but not flattened out with a hammer. The term **flexible** refers to the fact that the mineral bends easily and remains bent, while in contrast **elastic** means that the mineral after being bent returns to its original position. The micas are elastic while chlorite is flexible.

#### 4. Hardness

The resistance that a substance offers to abrasion is called hardness. It is not a property that is capable of exact definition or measurement, but comparative tests are expressed in terms of a so-called **scale of hardness**. The scale of hardness consists of ten minerals ranging from talc, a mineral which has a soapy feel and is very easily scratched by the finger nail, up to diamond, the hardest known substance. The minerals are numbered as follows:

1 Talc	Knife Blade
2 Gypsum	6 Orthoclase
Finger Nail	7 Quartz
3 Calcite	8 Topaz
4 Fluorite	9 Corundum
5 Apatite	10 Diamond

The finger nail is about  $2\frac{1}{2}$ , for it scratches gypsum, but is scratched by calcite. A knife blade is about  $5\frac{1}{2}$  for it scratches apatite, but is scratched by orthoclase. The hardness of a mineral is judged both by its effect on the minerals of the scale and their effect upon it. If a mineral scratches fluorite but is scratched by apatite, it has a hardness of  $4\frac{1}{2}$ . Two minerals of the same hardness will scratch each other.

Great care should be used in determining the hardness. A foreign substance embedded in the mineral will often give too high a value. A soft mineral leaves a chalk-mark on a harder one, so the mark left by a mineral should be a distinct groove. Minerals made up of grains or fibers often appear too low simply because the particles are forced apart. Thus a sandstone made

up of sand grains with hardness of 7 may appear to have a hardness of about 3 because the grains are rather loosely cemented. The value recorded in the description of minerals is the maximum value for crystallized varieties. For example, hematite in crystals has a hardness of 6, but some massive varieties have a hardness of 3 or even less.

In some minerals the hardness varies with the direction, as it does for all theoretically. Cyanite in a direction parallel to the *c*-axis has a hardness of  $4\frac{1}{2}$ , while at right angles to this the hardness is about 7. For most faces calcite has a hardness of 3, but on the basal pinacoid (0001) the hardness is about 2, being scratched by the finger nail.

### 5. Etch-figures

An important method of determining the symmetry of a crystal is by means of etch-figures. When a crystal is acted upon by a solvent, the action is not uniform, but begins at certain points and proceeds more rapidly in some directions than in others. If the action is stopped at the right time the faces of the crystal are usually found to be covered with little angular figures of definite shape and orientation called **etch-figures**. The etch-figures are usually shallow depressions bounded by minute faces. The fact that these faces are often general forms enables one in many cases to determine the crystal class. Examples are given in Figs. 129, 146, and 147. Without etching it would have been impossible to assign these substances to their proper crystal class. The shape of the etch-figures varies with the solvent, time, and temperature, but whatever their shape they always conform in symmetry to the class to which the crystal belongs. On similar faces the etch-figures are alike and on dissimilar faces they are unlike. The faces of etch-figures lie in well developed zones, but they have high indices. There is no rule to follow in obtaining etch-figures as it is simply a question of ease of solution. Crystals soluble in water may give them by passing a moistened

cloth over the surface while some refractory minerals, such as topaz, require fused caustic potash.

## 6. Specific Gravity

The density of a substance compared with the density of water under standard conditions (4° C.) is called the **specific gravity**. A specific gravity of 3 means that the substance weighs three times as much as an equal volume of water. The specific gravity is the weight of a substance divided by the weight of an equal volume of water. Five methods of finding the specific gravity are described.

(a). A rough, but rapid, method is to weigh out a gram of the mineral and then to find its volume with a burette, care being taken to eliminate air-bubbles. If one gram is used the specific gravity is the reciprocal of the volume.

(b). A more accurate method is based on the fact that a body immersed in water loses in weight an amount equal to the weight

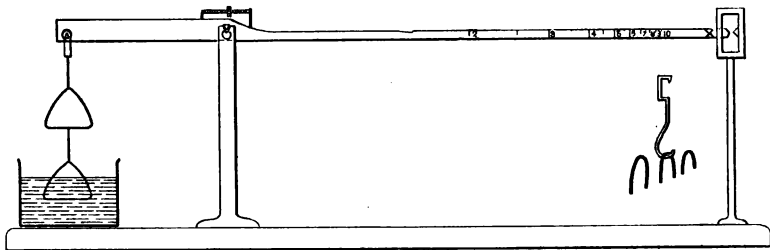


FIG. 309.—Specific gravity balance.

of the water displaced. The substance has the weight  $A$  in air, say. Suspended by a fine thread in a vessel of water, it has the weight  $W$ . Then  $G = \frac{A}{A-W}$ ,  $G$  being the specific gravity. Numerous precautions must be taken to insure accuracy.

(c). The most **convenient specific gravity balance** for the practical identification of minerals is that represented in Fig. 309 which was designed by the author and is used in his laboratory. It con-

sists essentially of a brass or wooden beam supported near one end by a knife edge. The short arm carries two pans, the lower one to be immersed in water. The end of the long arm rests within a guard, which limits the motion of the balance. The long arm of the beam is graduated so that the specific gravity may be read off directly. This may be done by always placing the counterpoise in the notch near the end of the long arm when weighing in air. Whatever the weight of the counterpoise its distance ( $x$ ) from the fulcrum, and the distance ( $y$ ) of the counterpoise from the fulcrum when weighing in water are connected by the equation,

$$G = \frac{x}{x-y}, \quad G \text{ being the specific gravity.}$$

The distance  $y$  for various values of  $G$  is marked on the beam. Thus in the balance figured,  $x$  is 15 inches. Then if  $G$  is 2,  $y$  is 7.5. So 2 is marked at a point 7.5 inches from the fulcrum. If  $G$  is 3,  $y$  is 10. So 3 is marked at a point 10 inches from the fulcrum. The balance is adjusted by a device just above the fulcrum. When in adjustment the balance will look like the figure, the lower pan being immersed in water and the long arm of the balance free. The mineral is placed on the upper pan and the counterpoise in the notch near the end of the long arm. Wire loops are added to the hook of the counterpoise until the mineral is balanced. Then the mineral is transferred to the lower pan. It is well to moisten the mineral before immersion so as to rid it of air bubbles. The mineral will lose weight so the counterpoise is moved toward the fulcrum until balance is restored. *The specific gravity is indicated directly on the beam.* This method is rapid and the results are accurate enough for the practical purposes of determination.

(d) For accurate work a pycnometer or specific gravity flask may be used. The pycnometer itself is first weighed ( $A$ ). The coarsely powdered mineral is introduced into the pycnometer and another weighing ( $B$ ) made. The flask is then filled with distilled water, air bubbles being eliminated by boiling. After cooling, the weight ( $C$ ) is taken. Then the flask is emptied and filled with distilled water, weight ( $D$ ). Then  $G = \frac{B-A}{D+B-A-C}$ . With

proper precautions this method is very accurate. Fibrous or porous minerals should be finely powdered, otherwise the value is too low.

(e) A number of heavy liquids are useful in determining the specific gravity. Methylene iodid,  $\text{CH}_2\text{I}_2$ , has a specific gravity of 3.3 and may be diluted with benzol (sp. gr. = 0.98), forming a liquid with any desired intermediate specific gravity. A water solution of potassium mercuric iodid,  $\text{KI} \cdot \text{HgI}_2$ , also called Thoulét solution, has a specific gravity of 3.19 and may be mixed with water in any proportion. The specific gravity of a mineral may be determined by diluting these liquids until fragments of the mineral neither sink nor float, but remain suspended. A Westphal balance is used to determine the specific gravity of the liquid. The heavy liquids are especially useful in separating mixtures of minerals for the purpose of analysis.

A table showing the specific gravities of the common and important minerals is given on pages 229-232.

## 7. Luster

**Luster** is the term applied to the quality of light reflected from a substance. **Metallic luster** is the brilliant luster of metals possessed by most sulfid minerals such as galena, pyrite, etc., as well as some oxids such as hematite and magnetite. Minerals with metallic luster are opaque even on the thinnest edges.

**Adamantine** is the brilliant luster of transparent or translucent minerals with high index of refraction. Examples are diamond ( $n=2.41$ ) and cerussite ( $n=1.80-2.07$ ). **Vitreous** is the luster of broken glass possessed by most transparent or translucent minerals such as quartz, calcite, etc. **Pearly** luster is due to continued reflection from a series of parallel plates and is possessed by minerals with eminent cleavage such as gypsum and talc. **Silky** luster is due to fibrous structure and is illustrated by fibrous serpentine and fibrous gypsum. Waxy, greasy, pitchy, and dull are self-explanatory terms used to describe luster.



### 8. Color

In some minerals such as cinnabar, orpiment, malachite, and azurite the color is a property of the substance and hence is constant. The color of a metallic mineral is always quite constant, but as these minerals are susceptible to tarnish a fresh fracture should always be observed.

But in the majority of non-metallic minerals the color is due to some impurity which usually exists in very small amounts and varies in different localities. Thus quartz, calcite, and fluorite, if pure are colorless, but they are found in practically all colors and the color may even vary in the same specimen.

A table for determining minerals by color will be found on pages 223-227.

### 9. Streak

The **streak** of a mineral refers to the color of its powder. It may be determined by rubbing a corner of the mineral on a piece of unglazed porcelain called a **streak-plate**. In the absence of a streak-plate a smooth piece of light colored flint or chert may be used. A thin slab of novaculite also makes an excellent streak-plate.

The streak, though colorless for most non-metallic minerals and dark-gray or black for many metallic ones, is especially valuable in the determination of a few common minerals such as hematite (streak, red-brown), and limonite (streak, yellow brown).

## PART III

### THE OPTICAL PROPERTIES OF MINERALS

Among the physical properties the optical properties take first rank in the accurate description and determination of minerals.

Most of the optical determinations can be made by means of a special form of microscope known as the polarizing microscope, but for the more accurate determination of the optical constants the refractometer, the goniometer, and the axial angle apparatus must be used.

Minerals for optical determinations may be prepared in three different forms: (1) oriented sections or sections cut in definite crystallographic directions, (2) thin rock sections by means of which minerals in fine grained rocks may be determined, and (3) fragments, cleavages, and minute crystals. As fragments are easily prepared simply by crushing the mineral, the method is a general one for the examination of all but opaque minerals. *The polarizing microscope should have a place in the mineralogical laboratory and should supplement the blowpipe in the determination of minerals.*

#### 1. THE NATURE OF LIGHT

It is now generally believed that light consists of a vibratory motion or some kind of disturbance in the ether, a hypothetical medium which is supposed to pervade all space and even material bodies. The wave-motion, as it is called, is regarded as the resultant of simple harmonic motion and a uniform motion at right angles to this. Fig. 310 explains the **wave-motion**. Simple harmonic motion is uniform motion in a circular path as it would appear on a diameter of the circle. A point moving from

$a$  to  $d$  appears to move from  $a'$  to  $d$ . This constitutes a periodic vibration with varying velocity which may be represented by the swinging of a pendulum. If this is compounded with linear motion from  $A$  to  $A'$  we have the harmonic curve  $ADGJA'$ , which is a sine curve represented by the equation  $y = a \sin \frac{2\pi}{T}x$ , in which  $a$  is  $OD$ , called the amplitude, and  $\frac{2\pi}{T}$ , the angular velocity in the circle.

Thus light consists, to the best of our knowledge, of a periodic vibration (or some kind of disturbance in the ether) transverse to the direction of transmission, though we know nothing of its physical nature. It may be illustrated by the waves observed along the sea-shore. A floating object, in general, simply moves up and down, while the wave as a whole advances toward the shore.

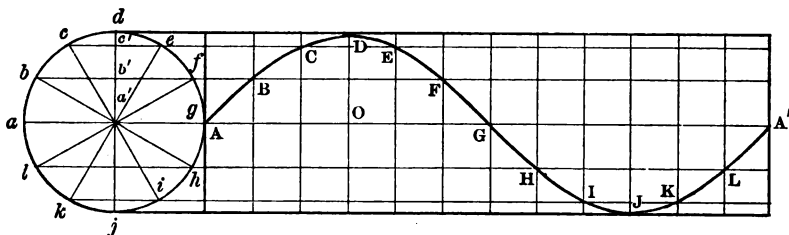


FIG. 310.—Wave motion.

The maximum displacement,  $OD$  (Fig. 310), is called the **amplitude** of the vibration.

The point with the maximum upward displacement,  $D$ , is called the **crest** of the wave and the point with maximum downward displacement,  $J$ , the **trough**. The distance between two successive crests or troughs, or a corresponding distance such as  $AA'$ , is called the **wave-length** (denoted by the Greek letter,  $\lambda$ ).

By **phase** is meant the position of any point and the direction in which it is moving. Two points are in the **same phase** when

they are in the same relative position and moving in the same direction. The **phase difference** of two points is the distance apart of their ordinates in terms of the wave-length.

A **ray** of light is a line to indicate the direction of transmission of the wave motion. A **wave-front** is the surface determined by all the parts of a system of waves which are in the same phase. A ray is perpendicular to its wave-front.

The intensity of light depends upon the amplitude of the vibrations, and the color of the light depends upon the wave-length of the vibrations. The wave-length for the violet end of the spectrum is  $380\mu\mu$  (millionths of a millimeter) and for the red end of the spectrum,  $760\mu\mu$  (millionths of a millimeter). White light is the sum of light of various wave-lengths. For this reason **monochromatic light** (light of approximately one wave-length) must be employed in all accurate optical work. The simplest method of obtaining monochromatic light is to ignite a sodium, lithium, or thallium salt on platinum wire by which is produced yellow ( $589\mu\mu$ ), red ( $670\mu\mu$ ), or green ( $535\mu\mu$ ) light respectively. The sodium salt is the one most frequently used.

## 2. REFRACTION OF LIGHT

When light passes from one medium into another, in general there is a change of direction. This is known as **refraction**. A familiar illustration is the apparent bending of a stick in water. In Fig. 311 the angle  $i$  is called the *angle of incidence* and the angle  $r$ , the *angle of refraction*. There is found to be a constant relation between the sines of these angles and whatever the direction of transmission,  $\frac{\sin i}{\sin r} = n$  (a constant). The constant,  $n$ , which is called the **index of refraction**, depends upon the substance and upon the kind of monochromatic light used. The index of refraction for the violet end of the spectrum is greater than for the red end of the spectrum as shown in Fig. 312. The following

table gives the indices of refraction (yellow light) for some of the common minerals:

Fluorite	1.43
Quartz	1.55
Apatite	1.63
Garnet	1.76
Sphalerite	2.37

Substances with a high index of refraction (1.9 or over) have the brilliant appearance called adamantine luster, while minerals with lower index of refraction have ordinary vitreous luster.

Several particular directions of transmission should be mentioned. In the formula  $\frac{\sin i}{\sin r} = n$ , if  $i = 0^\circ$ ,  $r = 0^\circ$ ; so for normal incidence there is no refraction. If  $i = 90^\circ$ , the equation becomes  $\sin r = \frac{1}{n}$ ;  $r$  for this particular value is called the **critical angle**.

The critical angle is a constant for the substance. A graphic determination of this angle is shown in Fig. 313. The indices

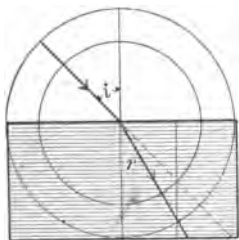


FIG. 311.

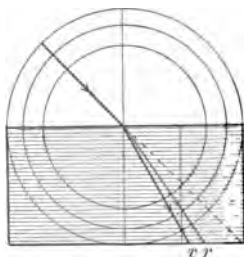


FIG. 312.

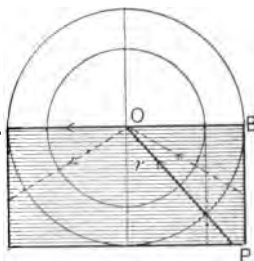


FIG. 313.

of refraction of the two substances are the radii of two concentric circles, AB being the boundary between the two substances. A tangent is dropped from the intersection of the inner circle with the boundary line. A radius is then drawn through the point where this tangent intersects the outer circle. The angle  $r$  is the critical angle.

Rays of light passing from the denser (lower) medium to the

rarer (upper) medium along the line PO will graze the surface OA. Rays of light passing from the denser into the rarer medium at angles greater than the critical angle cannot enter the rarer medium, but are reflected back into the denser medium as illustrated by the dotted line of Fig. 313. This phenomenon is called **total reflection**. An empty test-tube immersed in a beaker of water has a peculiar silvery appearance because of total reflection. This silvery reflection disappears when the test-tube is filled with water.

The great brilliancy of the cut diamond, as compared with natural crystals of the uncut diamond, is due principally to the fact that the facets are arranged so that most of the light is totally reflected, the critical angle for diamond being very small ( $24^\circ$  as compared with  $48^\circ$  for ordinary glass).

The simplest means of determining the index of refraction of a mineral is by means of the **Becke test**. Fragments of the mineral are embedded in a liquid of known index and examined on the stage of a microscope with the substage lowered. On focusing sharply on the edge of the mineral and then throwing it slightly out of focus by raising the microscope tube, a blurred white line will appear on the side of the substance having the greater index of refraction. On lowering the microscope tube the white line appears on the side of the substance having the smaller index of refraction. By using a number of liquids the index may be obtained within certain limits. The most useful liquids are as follows:

Water	1.33
Oil of cloves	1.53
Bromoform	1.59
$\alpha$ -Monobromnaphthalin	1.66
Methylene iodid	1.74

The Becke test may be explained by referring to Fig. 314. S and S' are two substances in contact along a vertical boundary, S' having the greater index. A cone of light rays from the

mirror passes upward through the two substances. Light will go from each substance into the other. The rays 1 to 6 will all go into the denser medium  $S'$ . Of the rays 7 to 12, 10 to 12 will go from the denser substance  $S'$  into the less dense substance  $S$ , while the rays 7 to 9 will be totally reflected, provided the critical angle is such that a ray between 9 and 10 grazes the boundary. Then

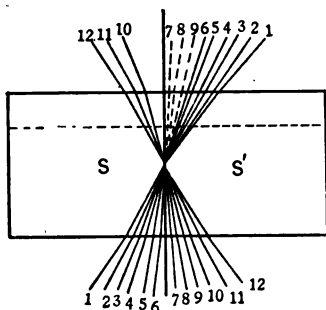


FIG. 314.—Explanation of Becke test.

on changing the focus slightly to the dotted line shown in the figure, there is a concentration of light on the side of the denser substance  $S'$ , which constitutes the white line.

The index of refraction may also be judged by the appearance of the fragment in the liquid. If the fragment and the liquid have about the same index of refraction, the fragment will appear smooth and will scarcely be visible. This is called **low relief** (Fig. 316). If, on the other hand, the indices of refraction of the two substances are quite different the surface of the fragment

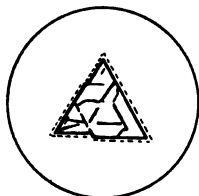


FIG. 315.

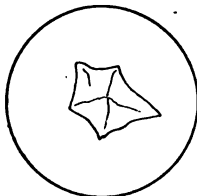


FIG. 316.

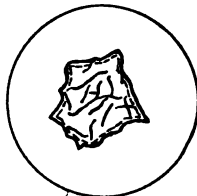


FIG. 317.

will appear rough and the borders dark. This is called **high relief**. It should be noted that the fragment will have high relief whether its index is less (Fig. 315) or greater (Fig. 317) than that of the liquid.

### 3. POLARIZED LIGHT

The light transmitted through a slice of a colored tourmaline crystal cut parallel to the *c*-axis has acquired peculiar properties as may be seen by allowing the light from one tourmaline to fall upon another similar tourmaline. When similar directions of the two tourmalines are parallel, a maximum amount of light is transmitted, while if similar directions of the tourmalines are perpendicular no light at all is transmitted. The simplest explanation is that the light is vibrating in one plane only. Whether the vibration plane is the plane of the *c*-axis or a plane perpendicular to this we do not know, but we may assume it to be the plane of the *c*-axis.<sup>1</sup>

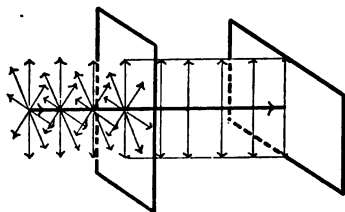


FIG. 318.—Polarisation by absorption.

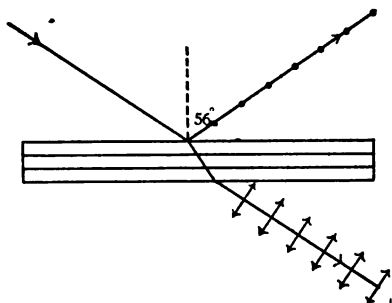


FIG. 319.—Polarization by refraction.

In ordinary light the vibrations are in all planes, while the light transmitted by the tourmaline slice is in but one plane. This light is known as **polarized light**. Fig. 318 is a diagrammatic representation of ordinary light and polarized light as transmitted by tourmaline.

The light reflected from non-metallic surfaces such as glass or polished wood is more or less polarized. If the light reflected

<sup>1</sup> Some physicists assume that the other plane is the vibration-plane. According to the electro-magnetic theory of light there are disturbances in both planes. In the plane of the *c*-axis there is an electrical disturbance, while in the other plane there is a magnetic disturbance.



from a sheet of glass is examined with the tourmaline, it will be found that for a certain angle of incidence light is almost extinguished when the *c*-axis of the tourmaline is parallel to the plane of incidence, while light is ~~fully~~ transmitted when the direction is perpendicular to the plane of incidence. This means that the reflected light is partially polarized, the plane of vibration being perpendicular to the plane of incidence as shown in Fig. 320.

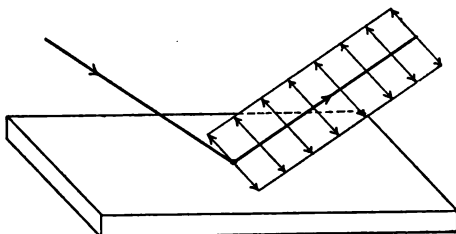


FIG. 320.—Polarization by reflection.

Another method of producing polarized light is by continued refraction through a series of parallel glass plates. The emerging light is partially polarized and vibrates in the plane of incidence. Fig. 319 shows this as well as the fact that the reflected light is polarized and vibrates in a plane normal to the plane of incidence.

The most practical method of obtaining polarized light is by means of a Nicol prism, but this involves a discussion of double refraction which is the next topic.

#### 4. DOUBLE REFRACTION

If a dot is viewed through a clear cleavage rhombohedron of calcite (Iceland spar) two images of the dot are seen and on revolution of the calcite one dot remains stationary, while the other dot appears to revolve around the fixed one. A ray of light gives rise to two rays, the **ordinary ray** (the fixed one) and the **extraordinary ray** (the one that revolves). In Fig. 321 the image of the ordinary ray is marked *o*, and that of the extraordi-

nary  $e$ . This phenomenon is known as **double refraction** and though possessed by most minerals, only in a comparatively few is it marked enough to be seen with the naked eye.

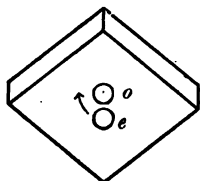


FIG. 321.

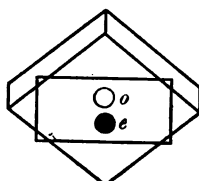


FIG. 322.

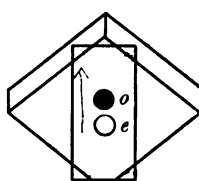


FIG. 323.

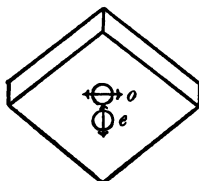


FIG. 324a.

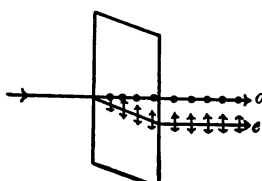


FIG. 324b.

FIGS. 321-324b.—Double refraction in calcite.

Light that emerges from a doubly refracting substance such as calcite has acquired peculiar properties as may be demonstrated by examining this double image with a tourmaline section cut parallel to the  $c$ -axis. When the  $c$ -axis of the tourmaline is



FIG. 325.



FIG. 326.

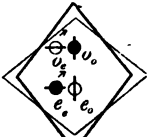


FIG. 327.



FIG. 328.



FIG. 329.

parallel to the long diagonal of the calcite rhomb (Fig. 322) only the image due to the ordinary ray,  $o$ , is seen, but when the  $c$ -axis of the tourmaline is parallel to the short diagonal of the calcite rhomb (Fig. 323) only the image due to the extraordinary

ray,  $e$ , is seen. Hence for the ordinary ray the vibrations are in the plane of the long diagonal and for the extraordinary ray the vibrations are in the plane of the short diagonal. See Figs. 324a and 324b.

If the double image formed by a piece of Iceland spar be viewed through another piece of Iceland spar, in general four images are visible, pairs of which wax and wane in turn as one of the Iceland spars is revolved. In certain positions  $90^\circ$  apart, only two images appear. Figs. 325–329 show diagrammatically the changes that take place. The symbols  $o$  and  $e$  refer to images produced by the first rhomb, while with the second rhomb  $o$  gives rise to  $o_o$  and  $o_e$ , and  $e$  to  $e_o$  and  $e_e$ .

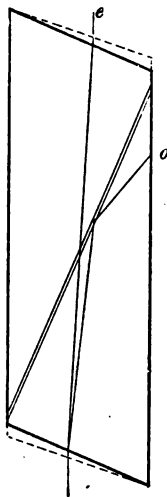
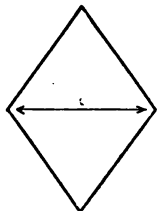


FIG. 330.  
Nicol prism.

This behavior is good evidence, if not proof, that in doubly refracting crystals light is polarized and is vibrating in two planes at right angles to each other. In Figs. 325–329 the short lines through the circles indicate the vibration planes.

## 5. THE NICOL PRISM

The principal device for producing polarized light is a **Nicol prism**, so-called from the name of its inventor, Nicol. It is a piece of apparatus to which we are indebted for much of our knowledge of crystal optics. A clear piece of calcite or Iceland spar (this variety is obtained almost exclusively from cavities in the basalt at a certain locality in Iceland) of suitable dimensions is cut through in a plane at right angles to the principal section and  $93^\circ$  to the terminal faces. After polishing, the two halves are cemented by Canada balsam and mounted. Fig. 330 represents a vertical cross-section of a Nicol prism together with a horizontal plan. Now as the refractive index of the ordinary ray of calcite

is 1.65 and that of the balsam about 1.54, it will be seen from the figure that the ordinary ray *o*, in passing from the calcite to the balsam cement does not enter the balsam, but is totally reflected, meeting the surface at an angle greater than the critical angle. The extraordinary ray, *e*, passes on through the balsam cement but slightly affected by the balsam, as for this particular direction of transmission they have almost the same index of refraction. So ~~that~~ there emerges from the upper surface of the nicol, plane polarized light with vibrations parallel to the short diagonal of the calcite rhomb as indicated in Fig. 330.

If a Nicol prism is examined with a tourmaline, darkness results when the *c*-axis of the tourmaline is parallel to the long diagonal of the calcite rhomb.

If two nicols have their short diagonals parallel, light goes through unaffected, save the intensity is diminished, but on revolving one of the nicols, the light gradually fades until their short diagonals are at right angles, when darkness results.

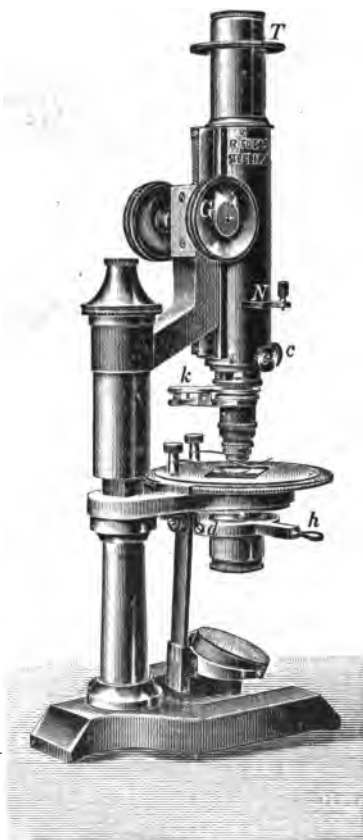


FIG. 331.—Polarizing microscope (1/4 size).

## 6. THE POLARIZING MICROSCOPE

The polarizing or petrographic microscope (Fig. 331) differs from an ordinary microscope in the addition of a rotating stage

for measuring angles and of two Nicol prisms one above, the other below, the stage. Two nicols are necessary, for the effects due to polarized light cannot usually be distinguished except by another nicol. The lower nicol is called the **polarizer** and the upper one, the **analyzer**. The lower one fits into a socket so it may be rotated, but ordinarily it is set so that its vibration plane is at right angles to that of the upper nicol. Then the field should be dark and the nicols are said to be crossed.

In some cases we use the lower nicol alone and then its vibration plane must be known. A cleavage fragment of calcite has high relief when its long diagonal is parallel to the plane of vibration of the nicol (see Fig. 364, p. 147).

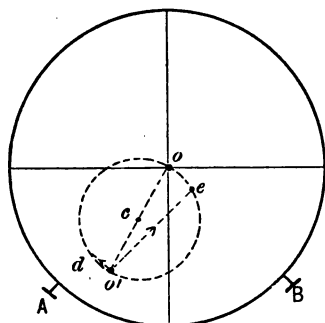


FIG. 332.—Centering the stage.

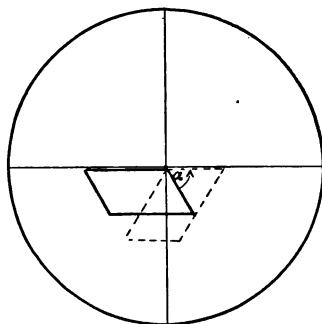


FIG. 333.—Measuring an angle.

In order to use the rotating stage, its center must coincide with the optical center of the microscope tube. The method of **centering the stage** may be explained by referring to Fig. 332. A and B are centering screws  $90^\circ$  apart, located either on the stage or on the microscope tube, preferably on the latter. The two perpendicular lines across the field represent the cross-hairs. An object, *o*, on a glass slide is placed at the intersection of the cross-hairs. Suppose on revolution of the stage it appears to revolve in the dotted circle until it resumes the position *o*. Then revolve the stage  $180^\circ$ , correct for one-half the error by the

centering screws, the other half by moving the slide on the stage. In the figure the error is  $oo'$ , the components of which in the direction of the cross-hairs are  $o'e$  and  $o'd$ . Then by the centering screw A,  $o'$  is first moved the distance  $\frac{1}{2}o'e$  and by the centering screw B,  $o'$  is moved the distance  $\frac{1}{2}o'd$ . The object,  $o$ , then takes the position  $c$  and the slide itself must be moved the distance  $co$ , when the stage should be centered.

To measure a plane angle in a thin section or the interfacial angle of a small, flat crystal the stage is centered with the intersection of the two edges at the center of the cross-hairs. A reading is made when one edge of the crystal is parallel to the east-west cross-hair, say, then the stage is revolved until the other edge (dotted line in Fig. 333) is parallel to the same cross-hair, but on the opposite side of the center, when another reading is taken. The difference between the two readings is the supplement or external angle ( $\alpha$  in the figure).

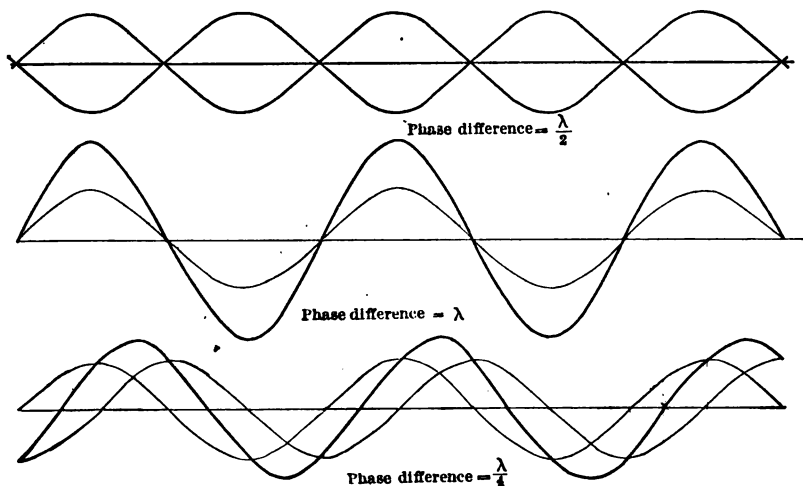
The microscope is often used for measuring very small distances such as the dimensions of minute crystals. For this purpose a special eye-piece (micrometer eye-piece) containing a scale etched on glass is used. On the stage of the microscope a scale reading hundredths of a millimeter is placed. It is then simply necessary to see how many hundredths of a millimeter each division of the eye-piece is equivalent to.

## 7. INTERFERENCE COLORS

If thin plates of singly refracting (isometric) crystals are examined between crossed nicols there is no result, for the original field remains dark. But if thin plates of doubly refracting crystals are examined between crossed nicols there result the beautiful color effects known as **interference colors**. In order to explain these colors it is necessary to consider the results obtained in examining the doubly refracting plates in monochromatic light. If two light waves or train of waves of the same wave-length travel along the same path, after they

have travelled different distances in another medium, they combine in general to produce a new wave, the abscissa at any point of which is equal to the sum of the abscissæ of the two original waves. This is called **interference**.

There are two special cases of importance. (1) The two waves have the same amplitude and a phase difference or path difference of  $\frac{1}{2}\lambda$ . As can be seen from Fig. 334 they neutralize each other and darkness is the result. That is, two light waves can



FIGS. 334-336.

combine so as to produce darkness. (2) The two waves have the same amplitude and a phase difference of  $\lambda$ . In this case the new wave will have the same phase, but the amplitude will be doubled (Fig. 335). For intermediate cases such as phase difference of  $\frac{1}{4}\lambda$ , the resultant wave will have an intermediate amplitude (Fig. 336). Interference results when light waves from the same source go over the same path one in advance of the other. There are two methods of obtaining interference, one by the use of thin films, the other by the use of doubly refracting crystals.

Let Fig. 337 represent a thin film of air in a selenite cleavage. AB and A'B' are oblique incident rays. On reaching the surface of the film they are partly reflected and partly refracted. So that for a point B' there will be two rays travelling along B'D'; one of them is the reflected ray of A'B', the other the refracted ray EC. These two rays are in a position to interfere for one of them has travelled a greater distance than the other. For while one has travelled A'B' the other has travelled ABE. Hence the ray from AB is the distance ECB' behind the ray from A'B'.

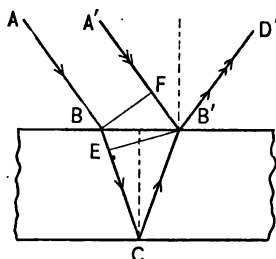


FIG. 337.

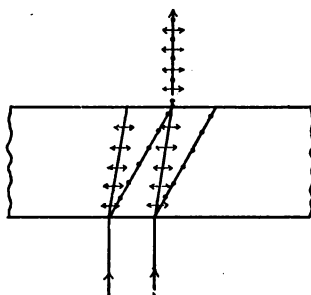


FIG. 338.

If we use monochromatic light and adjust the thickness of the film so that the retardation, or lagging of one ray behind the other, is equal to  $\frac{1}{2}\lambda$ , we have, for that particular thickness, darkness, while for a retardation of  $\lambda$  we have light of maximum intensity. So that with a wedge-shaped film in monochromatic light we have a series of dark bands, for retardations of  $\frac{n\lambda}{2}$  and  $n\lambda$  produce the same effect as  $\frac{\lambda}{2}$  and  $\lambda$  respectively.

Now let us consider the case of doubly refracting crystals. A series of parallel light waves from the polarizer or lower nicol enter the crystal and are broken up into two sets of waves one vibrating in the plane of the paper, say, and the other in the



plane normal to the paper. See Fig. 338. At certain points on the upper surface there will emerge points of waves travelling in the same path but vibrating in planes at right angles to each other, and oblique to the planes of vibration of the nicols. In order that they may interfere it is necessary to reduce the vibrations to one plane and for this purpose an analyzer or upper nicol is necessary. The effects produced depend upon the relative positions of the nicols, upon the position of the mineral with reference to the nicols, and upon the phase difference of the two sets of polarized light waves.

Fig. 339 explains diagrammatically what happens when a doubly refracting crystal is examined between the crossed nicols of a polarizing microscope. A ray of light entering the lower nicol is broken into two rays,  $e$  and  $o$ . One of these ( $o$ ) is totally reflected and disappears. The remaining ray ( $e$ ) is broken into two rays ( $e'$  and  $o'$ ) by the mineral plate. These two rays, which are vibrating at right angles to each other, are each broken into two rays ( $e''$ ,  $o''$ , and  $e'''$ ,  $o'''$ ), by the upper nicol. One from each of these ( $o''$  and  $o'''$ ) is totally reflected and finally there emerges from the top of the upper nicol two sets of waves ( $e''$  and  $e'''$ ) vibrating in the same plane and these interfere with each other.

With crossed nicols darkness results when the phase difference is  $\lambda$ . In Fig. 340  $PP'$  is the vibration plane of the lower nicol and  $AA'$  of the upper nicol,  $RR'$  and  $SS'$ , the

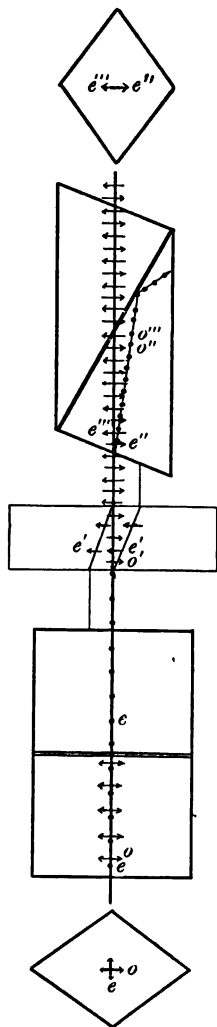


Fig. 339.

vibration planes of the crystal plates.  $r$  and  $s$  represent vibrations in the same phase. The components of these in the plane of the upper nicol are  $\rho$  and  $\sigma$ , which are opposite and equal. Hence they annul each other. With crossed nicols there is maximum light when the phase difference is  $\frac{1}{2}\lambda$ . In Fig. 342  $r'$  and  $s$  represent vibrations of  $\frac{1}{2}\lambda$  phase difference. Their components in the plane of the upper nicol are  $\rho'$  and  $\sigma$ , equal but on the same side of the origin. Hence the intensity is doubled.

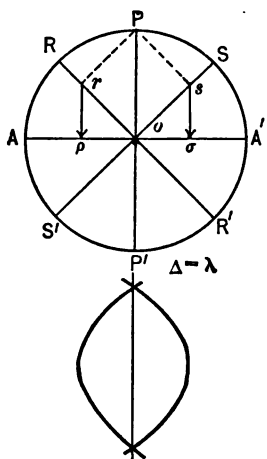


FIG. 340.

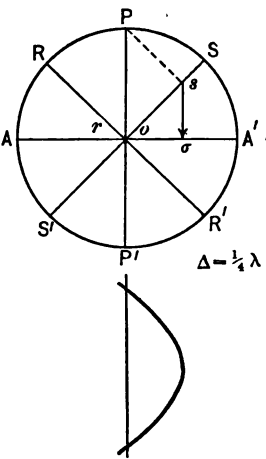


FIG. 341.

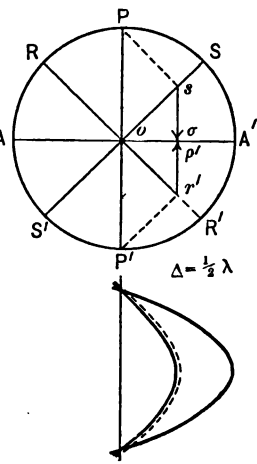


FIG. 342.

For a phase difference of  $\frac{1}{4}\lambda$ , we have the intensity shown in Fig. 341. Thus the intensity varies between 0 for a retardation of  $\lambda$ , and a maximum for retardation of  $\frac{1}{2}\lambda$ .

As can be seen from Fig. 343, the retardation produced by a wedge-shaped section of a crystal will vary from point to point.

A retardation of  $n\lambda$  will give darkness and a retardation of  $\frac{n}{2}\lambda$  will give a maximum intensity. Hence a wedge examined in monochromatic light between crossed nicols will appear as a series of

parallel dark bands interspersed with colored spaces, the color depending upon the monochromatic light used.

For white light we have the combined effect of all the colors of the spectrum. Some idea of the interference colors seen in white light may be gained by a study of Fig. 344. (This diagram may be colored by the student.) The top of the figure represents a wedge-shaped section as viewed in various kinds of monochromatic light, there being a dark band at positions which give retardations of  $n\lambda$ . For each of these colors a medium value of

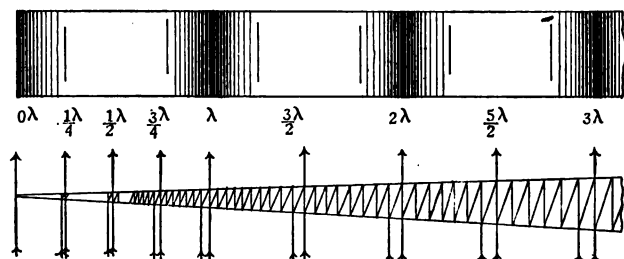


FIG. 343.

the wave length is chosen as follows: red,  $700\mu\mu$ ; orange,  $620\mu\mu$ ; yellow,  $560\mu\mu$ ; green,  $515\mu\mu$ ; blue,  $460\mu\mu$ ; violet,  $410\mu\mu$ . The top row of figures gives the value of retardations in  $\mu\mu$ .

The lower part of the figure indicates the interference colors as seen in white light. Let us consider the colors in succession. The intensity of different parts of the spectrum varies and has an influence in determining the color. Yellow is the most intense, and violet, the least intense part of the spectrum. The **color chart**, as it is called, begins with darkness, succeeded by dark gray which gradually becomes lighter. At about  $250\mu\mu$  all the colors combine to form white light. At  $280\mu\mu$  ( $\frac{\lambda}{2}$  for yellow) yellow is at a maximum, but mixed with white gives straw yellow. At  $310\mu\mu$  and at  $350\mu\mu$  orange and red respectively, are at a maximum, but

the great intensity of the yellow modifies these colors and places them further to the right, for at  $340\mu\mu$  the color is bright yellow. At  $575\mu\mu$  violet is the color. Though of weak intensity, violet is produced here because the other colors are practically extin-

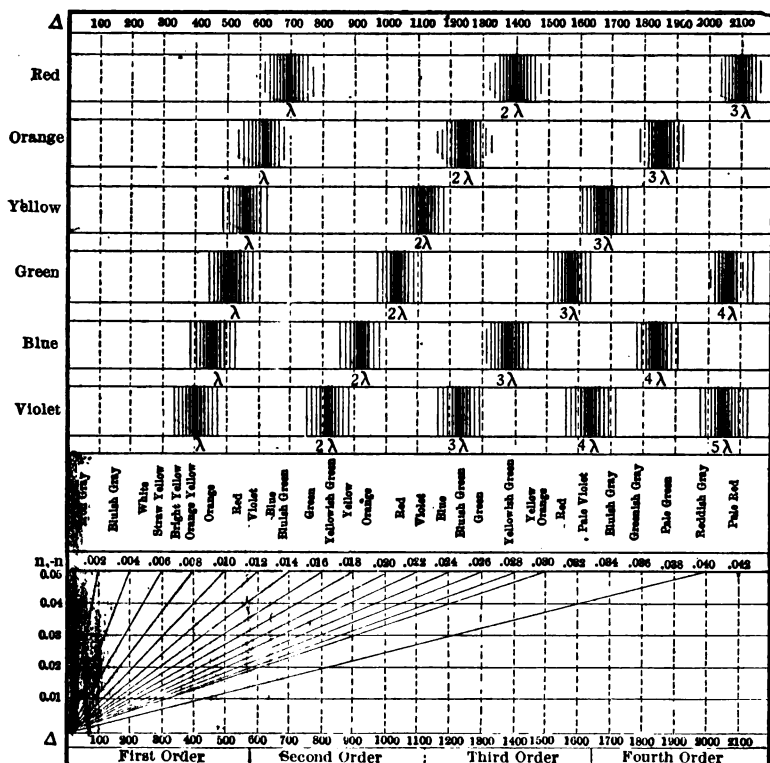


FIG. 344.—The color chart and its derivation.

guished. As can be seen from the diagram the colors follow in order: blue, green, yellow, and red. At  $1125\mu\mu$  violet appears again. At this point only red, blue, and violet are near a maximum. But red and blue together produce violet. Then in order.

we have blue, green, yellow, and red again. After this the colors are paler and pass into neutral tints and finally into white which resembles ordinary white light.

There is a repetition in the colors, but they gradually become fainter. The colors from black up to the first violet ( $\Delta = 575\mu\mu$ ) are called **first order** colors, from this violet up to the second violet ( $\Delta = 1125\mu\mu$ ), **second order** colors and so on. In white light six or seven orders may be distinguished, but in monochromatic light there is no limit to the number of orders as determined by the dark bands.

By trial it may be found that the interference color depends upon three factors: (1) the double refraction which is a constant for the crystal; (2) the orientation or direction in which the crystal is cut (in a thin section of sandstone the quartz grains, cut in various directions, have a great variety of interference colors); (3) the thickness as may be seen in a quartz or selenite wedge.

The formula  $\Delta = t(n_1 - n)$  gives the relation between  $\Delta$ , the retardation in  $\mu\mu$ ,  $t$ , the thickness of the plate and  $(n_1 - n)$ , the double refraction,  $n_1$  and  $n$  being the two values of the indices of refraction for a particular section. For a given substance with known indices of refraction the thickness may be measured and the interference colors predicted. Or the thickness may be measured, the retardation determined from the color chart, and the double refraction calculated. Or the thickness may be calculated that will give a certain interference color for a crystal with known double refraction. In the color chart at the bottom of Fig. 344, the horizontal lines represent the thickness from 0.00 to 0.05 mm., ordinary rock slides and fragments being from 0.03 to 0.05 mm. in thickness. The vertical lines give retardations in  $\mu\mu$  while the diagonal lines represent the amount of the double refraction. A crystal of 0.03 mm. thickness and double refraction of 0.02 has a retardation of  $600\mu\mu$  ( $0.000600 = 0.03 \times 0.02$ ), and gives a violet interference color.

## 8. VIBRATION OR EXTINCTION DIRECTIONS

If a section of a doubly refracting crystal is revolved between crossed nicols there is darkness four times in a complete revolution. This is called **extinction** and is simply due to the fact that for these particular positions the crystal has no effect upon the dark field produced by the crossed nicols. The two directions in the crystal parallel to the vibration planes of the two nicols are called **extinction directions** or vibration directions. These two directions are directions of the two plane polarized waves produced in doubly refracting crystals by the plane-polarized light of the lower nicol.

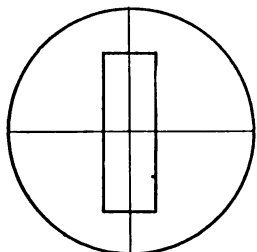


FIG. 345.  
Parallel extinction.

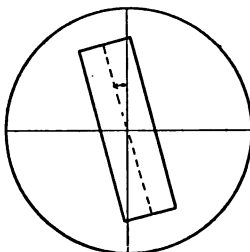


FIG. 346.  
Oblique extinction.

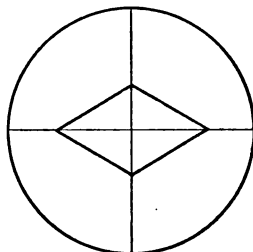


FIG. 347.  
Symmetrical extinction.

Now according to the position of these directions with reference to the crystal outlines we have various kinds of extinction which are characteristic of crystals of the various systems. In case the directions are parallel to the outline we have **parallel extinction**. This is represented by the convention of Fig. 345, the cross-hairs of the microscope being parallel to the vibration-planes of the nicols, and the crystal placed in the position of darkness. If the directions are not parallel to the outline we have **oblique extinction** (Fig. 346). The particular case in which these directions make equal angles with the edges of the crystal is called **symmetrical extinction** (Fig. 347).

The angle between an extinction direction and the prominent

edge of a crystal is called the **extinction angle**, and is characteristic of certain crystals in certain directions. The extinction angle is determined by taking a reading when the outline is parallel to one of the cross-hairs (the stage being centered) and then revolving the stage until maximum darkness results, when another reading is taken. The difference between the two readings is the extinction angle. In Fig. 346 the extinction angle indicated by the arrow is about  $15^\circ$ . It may be noticed that there are two possible extinction angles which are complementary. The smaller angle ( $< 45^\circ$ ) is usually taken.

Accurate determinations of the extinction angle are made in monochromatic light. A convenient determination in white light may be made by using a selenite plate which gives a field showing red of the first order. This is called the **sensitive tint**, the least change giving either orange-red or violet-blue. When inserted in the slot provided for test-plates a doubly refracting mineral appears the same tint of red as the red field only when in the extinction position.

## 9. DIRECTION OF THE FASTER AND SLOWER RAYS

For a section of a doubly refracting crystal cut in any direction there are in general two values of the index of refraction corre-

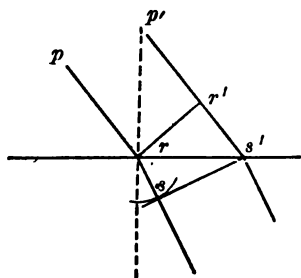


FIG. 348.—The relation of velocity to index of refraction.

sponding to the two vibration directions at right angles to each other. One of the values is greater than the other, otherwise there would be no double refraction. Interference is caused by one ray getting behind the other. This is the slower ray, the other being the faster ray. The ray with the greater index of refraction is the **slower ray** and the one with the smaller index of refraction is the **faster ray**, as may be proved by means of

Fig. 348. Parallel rays  $pp'$  on passing from air into a section

arrive at the points  $rr'$  together. But while the ray  $p'$  is going the distance  $r's'$  in air, the ray  $p$  has gone the distance  $rs$ , the velocity in the section being less than in air. The wave-front in the section is then  $ss'$  constructed by drawing a line from  $s'$  tangent to an arc with radius  $rs$  ( $rs$  being the velocity as compared with the velocity  $r's'$  in air). Thus there is a change in direction of the light rays. The rays are bent toward the perpendicular. Hence the section with velocity less than in air has an index of refraction greater than air.

It is often necessary to know which of the two directions is the slower ray. The determination of the extinction fixes the position of the two rays, but in order to determine which is which use is made of a section in which these directions are known. The superposition of one doubly-refracting section on another has the same effect as thickening or thinning the section by causing the interference colors to go up or down on the color chart, "up" being toward the thick end of a wedge and "down" toward the thin end of a wedge. Several **test-plates** are used for this purpose. The one most frequently used is the **mica plate**, a cleavage of muscovite of a thickness sufficient to produce a retardation of  $140\mu\mu$  ( $\frac{1}{4}\lambda$  for medium yellow and hence called the  $\frac{1}{4}$ -undulation mica plate). The direction of the slower ray of this plate is marked by an arrow. This direction is the line joining the branches of the hyperbola of the interference figure seen in convergent light. The mica plate itself gives a pale bluish-gray interference color of the first order and when placed in the slot provided for the purpose in the microscope tube causes the interference color of a crystal section placed in the position of maximum illumination to be lowered or raised by  $140\mu\mu$  (see color chart). The color goes up when similar directions are parallel (when slower ray of crystal coincides with slower ray of the mica plate) and down when dissimilar directions are parallel (when slower ray of crystal coincides with faster ray of the mica plate or vice versa).

This test is usually employed to determine the elongation of



the crystal, that is, to test whether the long direction of the crystal is the slower ray or the faster ray. Examples of the two cases are given in Figs. 349 and 350, the dotted rectangle representing the mica plate with arrow indicating the slower ray. In the first case, the crystal originally with red interference color is changed to blue, when its length is parallel to the arrow of the mica plate. Hence, the elongation is parallel to the slower ray.

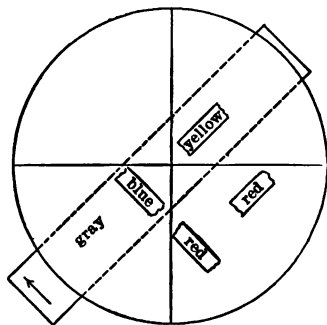


Fig. 349.—Positive elongation.

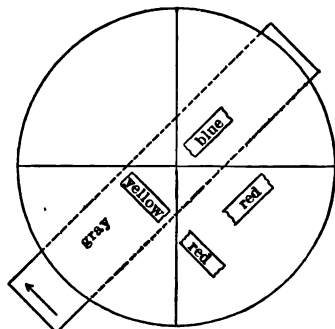


Fig. 350.—Negative elongation.

This is called **positive elongation**. In the other case, the red crystal is changed to blue, when its length is parallel to the faster ray of the mica plate, the faster ray being always perpendicular to the slower ray. This is called **negative elongation**.

## 10. CLASSIFICATION OF CRYSTALS FROM AN OPTICAL STANDPOINT

From an optical standpoint there are three divisions of crystals: isotropic (isometric), uniaxial (tetragonal and hexagonal) and biaxial (orthorhombic, monoclinic and triclinic). In discussing the optical properties it is convenient to employ a geometrical representation of the optical structure. The figure formed by taking as radius vector the index of refraction in various directions is called the **optical indicatrix**. The indicatrix is, in general, an ellipsoid, sections of which are ellipses. The important prop-

erty of the indicatrix is that the major and minor axes of any elliptic section are the extinction directions for that section and, moreover, the lengths of these axes are proportional to the indices of refraction for that particular section. The shape of the indicatrix varies for the three divisions of crystals mentioned.

In isometric crystals the index of refraction is the same for all directions. The optical indicatrix is therefore a sphere. All sections of a sphere are circular, so there is no double refraction and, hence, no interference colors. A section cut in any direction will remain dark between crossed nicols. Isometric crystals and amorphous substances such as glass are said to be **isotropic**. Crystals of the remaining systems (those except the isometric) have double refraction so that the term **anisotropic** is used for them in contrast with the term isotropic.

Tetragonal and hexagonal (also the trigonal if that is considered as a separate system) crystals constitute the **uniaxial** division. If sections of these crystals, cut in various directions, are examined between crossed nicols, it is found that basal sections (sections perpendicular to the  $c$ -axis) remain dark between crossed nicols and that all sections parallel to the  $c$ -axis give some interference color which is a maximum for a given thickness, while sections oblique to the  $c$ -axis give interference colors varying from a maximum to darkness, the color depending upon the obliquity, but those of equal obliquity around the  $c$ -axis give the same interference color.

From these tests it will be seen that the indicatrix is an ellipsoid of revolution. The axes of an elliptical section through the  $c$ -axis represent the indices of refraction, one of which designated  $n_\gamma$ , is the maximum of all possible values in the crystal, while the other, designated  $n_\alpha$ , is the minimum of all possible values. In some cases  $\gamma$ ,<sup>1</sup> or the slowest ray, is the  $c$ -axis, while in other cases,  $\alpha$ , or the fastest ray, is the  $c$ -axis. This divides the uniaxial crystals into two divisions, the **optically positive** ( $c = \gamma$ ) and the

<sup>1</sup>  $\alpha$ ,  $\beta$ , and  $\gamma$  are directions in a crystal and  $n_\alpha$ ,  $n_\beta$ , and  $n_\gamma$  are indices of refraction for these directions.

**optically negative** ( $c = \alpha$ ), the terms positive and negative being purely arbitrary. The indicatrix of positive crystals is an **oblate** spheroid and that of negative crystals, a **prolate** spheroid.

The determination of the **optical character**, that is, whether positive or negative, is made by ascertaining the faster and slower ray in a section parallel to the  $c$ -axis, or in a basal section by testing the interference figure, obtained by convergent light, with a mica plate.

Crystals of the remaining systems, orthorhombic, monoclinic, and triclinic, constitute the **biaxial** division. Of all the possible values of the indices of refraction in a biaxial crystal it is found that one section contains the direction  $\gamma$  corresponding to the maximum index of refraction  $n_\gamma$  and also the direction  $\alpha$  corresponding to the minimum index of refraction  $n_\alpha$ . For other sections the indices of refraction are intermediate between the maximum and minimum. The direction perpendicular to the plane of  $\gamma$  and  $\alpha$  is called  $\beta$  or sometimes the **optic normal**. The index of refraction  $n_\beta$  is intermediate between  $n_\gamma$  and  $n_\alpha$ , but is *not* a mean value.

The indicatrix for biaxial crystals made by laying off on three rectangular axes the values  $n_\alpha$ ,  $n_\beta$ , and  $n_\gamma$  or indices of refraction for the three directions mentioned is a triaxial ellipsoid. The maximum interference color for a given thickness is given by the section which includes  $\gamma$  and  $\alpha$ . The interference colors vary from this maximum to a minimum, but there is no section that remains dark between crossed nicols as in uniaxial crystals.

Fig. 351 is the section of a triaxial ellipsoid which contains  $\gamma$  and  $\alpha$ . There are two circular sections of this ellipsoid. Lines normal to these circular sections are peculiar directions corresponding somewhat to the single direction or  $c$ -axis of uniaxial crystals. These directions are called **optic axes**, hence the term biaxial. A plate normal to an optic axis appears uniformly bright between crossed nicols for all positions of rotation. The optic axes always lie in the plane of  $\gamma$  and  $\alpha$ , which is called the **plane of the optic axes** or the axial plane, and the acute angle

between the optic axes is called the **axial angle**, denoted by the term  $2V$ . In Fig. 351 OA and OA' are the optic axes and AOA' the axial angle. The optic axes are always symmetrically placed with respect to  $\gamma$  and  $\alpha$ . The line bisecting the axial angle is called the **acute bisectrix**, denoted by  $Bx_a$ . The line bisecting the obtuse angle between the optic axes is called the **obtuse bisectrix**, denoted by  $Bx_o$ .

There are two divisions of biaxial crystals according to whether the acute bisectrix is  $\gamma$  or  $\alpha$ . The former are called **positive** ( $Bx_a = \gamma$ ) and the latter, **negative** ( $Bx_a = \alpha$ ), a purely arbitrary designation. Fig. 351 represents a positive crystal.

The determination of the optical character may be made by testing for the faster and slower ray in a section known to be perpendicular to the acute bisectrix. It may also be determined in this kind of section by obtaining an interference figure and testing it with a mica plate.

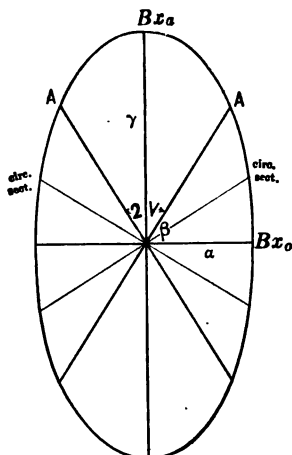


FIG. 351.

## 11. INTERFERENCE FIGURES

The tests mentioned up to this have been made by using ordinary **parallel light** or polarized parallel light. A unique series of effects, important in the identification and description of minerals, may be obtained by examining suitable sections in **convergent polarized light**. For this purpose either a polariscope or a polarizing microscope may be used. A **polariscope**, Fig. 352, is an instrument consisting essentially of an analyzer and polarizer with slight magnifying power and strongly convergent lenses both above and below the stage.

If the polarizing microscope is used, a high power objective (No. 7 Fuess, No. V Seibert, or  $\frac{1}{8}$  Bausch and Lomb), and also a

condensing lens placed just below the stage must be substituted for the ordinary set-up. Either the eye-piece must be removed or a special lens, called the Bertrand lens, must be inserted in the microscope tube between the upper nicol and the eye-piece.

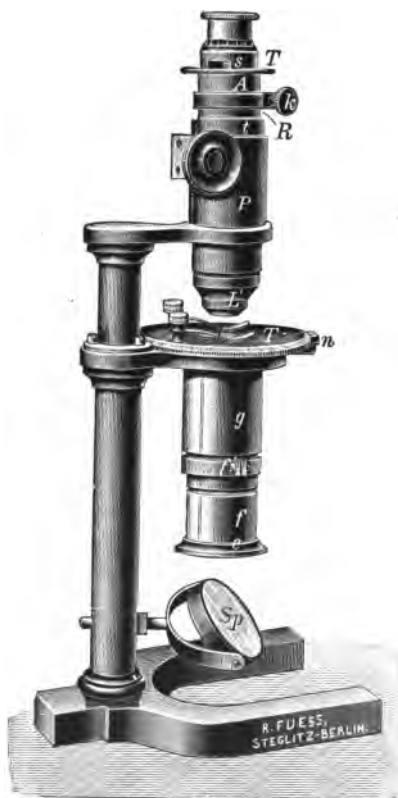


FIG. 352.—Polariscope (1/3 size.)

The color effects seen when basal sections of uniaxial crystals and sections of biaxial crystals cut normal to the acute bisectrix are examined in convergent light between crossed nicols are known as **interference figures**.

With isometric crystals no interference figures are obtained for there is no double refraction. Double refraction is necessary for the production of interference figures. In fact, interference figures are simply the result of interference colors, due to varying double refraction in different directions, combined and modified by the darkness due to crossed nicols.

Basal sections of uniaxial crystals examined in monochromatic convergent light between crossed nicols give a dark cross with dark concentric rings (Fig. 353). The

explanation is simple (see Fig. 356). Strongly convergent rays of light traverse the crystal in various oblique directions and the effect is the same as if rays of parallel light traverse a wedge of the crystal. So that along any radius we get a dark band where

the retardation is  $n\lambda$  for the particular light used. Midway between the bands we get the maximum color. As the structure is the same all around the  $c$ -axis in uniaxial crystals the dark bands are circular. It remains to explain the dark cross which it should be noticed is stationary on rotation of the section on the stage. The crystal, it may be imagined, is made up of innumerable parts each with extinction directions at right angles. These parts are arranged radially around a center and on rotation of the stage as vibration directions of successive parts become parallel to the vibration directions of the nicols,



FIG. 353.

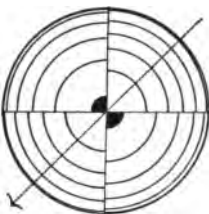


FIG. 354.



FIG. 355.

darkness results for that particular part. As new radii are always coming into extinction there is always a dark cross, the arms of which are parallel to the vibration directions of the two nicols and so remain fixed.

For sections not quite parallel to the basal plane the dark cross on rotation of the stage is eccentric, but the arms always remain parallel to the vibration planes of the nicols and revolve in the same direction in which the stage is rotated (see Fig. 355).

With ordinary white light we still have the black cross, but the dark rings become colored rings, the colors of which vary from black at the center through gray, yellow, red, and so on until after six or seven orders there is practically white light. The number of rings depends upon the thickness and also upon the double refraction. In very thin sections there may be no rings visible. Very thick sections show the full number of rings.

Quartz with weak double refraction shows for ordinary thickness no rings at all, while calcite with very strong double refraction shows a large number of rings.

The optical character of a uniaxial crystal may be determined from the interference figure by inserting in the slot a mica plate with the slower ray,  $\gamma$ , in the  $45^\circ$  position. The interference figure

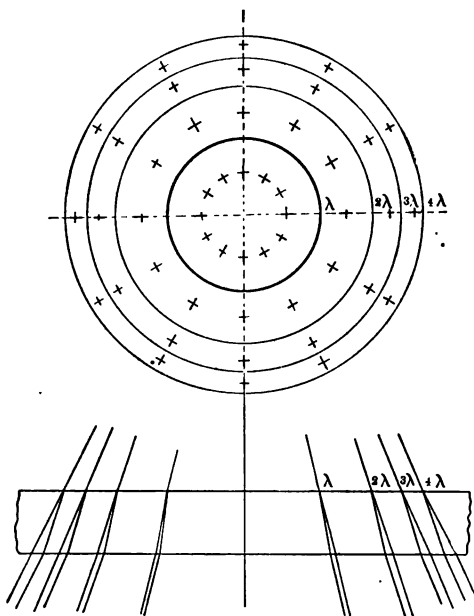


FIG. 356.

is changed, the dark cross disappearing and two dots appearing in two opposite quadrants as represented diagrammatically in Fig. 354. If the imaginary line joining the two dots is perpendicular to  $\gamma$  of the mica plate, the crystal is positive (Fig. 354), while if parallel to  $\gamma$  of the mica plate, it is negative. This is due to the fact that the interference colors "go up" in two opposite quad-

rants and "go down" in the other two quadrants. The rings then are not continuous, but broken and the two rings nearest the center are the two dots.

Sections of biaxial crystals cut normal to the acute bisectrix show an interference figure something like Fig. 357, with a black cross and two sets of concentric ellipses passing into 8-shaped curves or lemniscates. In monochromatic light the rings are dark and in white light colored. On revolving the section on the stage the dark cross opens up and passes into an hyperbola as

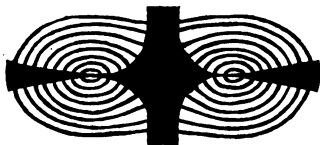


FIG. 357.



FIG. 358.

FIGS. 357 and 358.—Biaxial interference figure.

shown in Fig. 358, which represents the  $45^\circ$  position. The line joining the centers of the ellipses is the trace of the axial plane, the center of the ellipses representing the emergence of the optic axes. Hence the distance apart of the branches of the hyperbola is a measure of the axial angle. If these are close together the axial angle is small, if far apart the axial angle is large. If the axial angle is too large, the hyperbola does not appear at all using No. 7 Fuess objective.

The biaxial interference figure may be explained by means of the diagrammatic Fig. 359. The optical structure of biaxial crystals is symmetrical to three planes at right angles to each other. One of these is the plane of the paper, while the other two are represented by their traces, the vertical and horizontal lines of the figure, which are also vibration planes of the two



nicols. The two small circles are traces of the optic axes. The extinction directions for various parts of a crystal may be obtained by bisecting, internally and externally, the angles formed by joining any point with the traces of the optic axes. The dotted lines represent this procedure for one point. In similar manner the small crosses were obtained for different parts of the crystal. In the normal position a black cross will be formed along the vertical and horizontal lines. On revolving the section the black cross disappears. In the  $45^\circ$  position an hyper-

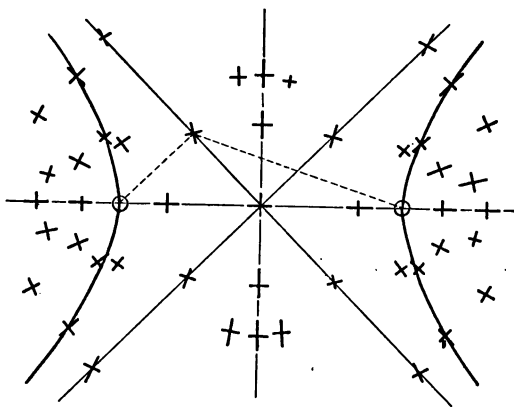


FIG. 359.—Explanation of a biaxial interference figure.

bola is formed by the darkness of different parts along the hyperbola as can be seen from the figure. In the  $90^\circ$  position the cross is restored.

The number of rings depends upon the strength of the double refraction and upon the thickness, but the distance between the branches of the hyperbola remains constant whatever the thickness.

The optical character is determined by means of a quartz wedge on which is marked the slower ray  $\gamma$ . The quartz wedge is inserted in the slot thin end first when the interference figure shows hyperbolæ. Then when  $\gamma$  is parallel to the trace of the

axial plane the ellipses appear to expand for positive crystals and to contract for negative crystals.

A section normal to an optic axes shows a series of concentric rings crossed by a dark bar which revolves in an opposite direction from the rotation of the stage.

## 12. OPTICAL PROPERTIES OF TWIN-CRYSTALS

One-half of a twin crystal has the same position with respect to the other half that it would have if rotated  $180^\circ$  about an axis from its original position. From this it can be seen that the extinction angles in two halves of a twin crystal are equal, but opposite in sign, if the section is cut normal to the twin-plane. Thus in a cleavage of a selenite twin the extinction directions are inclined to each other. Consequently if examined between



FIG. 360.



FIG. 361.

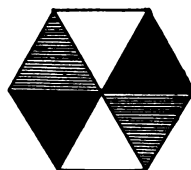


FIG. 362.

crossed nicols one-half of such a crystal is dark, while the other half is light (see Fig. 360). On rotation the light and dark parts interchange.

A section of a polysynthetic twin such as plagioclase shows a series of dark and light bands, the extinction directions in alternate bands being parallel (see Fig. 361).

Many orthorhombic crystals such as aragonite and  $K_2SO_4$  are pseudo-hexagonal by twinning, and basal sections between crossed nicols are divided into six sectors like Fig. 362, opposite pairs of which extinguish together. Basal sections of aragonite, like Fig. 362, examined in convergent polarized light show a biaxial

interference figure in each sector but arranged so that the axial planes are parallel to the outline. An optical examination reveals the composite nature of many apparently simple crystals.

### 13. ABSORPTION AND PLEOCHROISM

The color of a transparent substance is due to the residual color of the spectrum left after the substance has absorbed a certain part of it. Many colored anisotropic crystals have the property of absorbing different amounts or kinds of light in different directions. **Absorption** has reference to the amount or intensity of light absorbed and hence may be tested in monochromatic light while **pleochroism** refers to the kind of light absorbed and so must necessarily be tested in white light.

A prismatic crystal of epidote from the Sulzbachthal in Tyrol, if not too thick, will appear green in a certain position, while on revolving it  $90^\circ$  about its long axis it will appear brown. Few



FIG. 363.—Dichroscope.

substances show such a marked change as this, and at any rate it is not always possible to turn a crystal about and look through it in various directions.

The determination of pleochroism and absorption is made either by means of one nicol of a polarizing microscope in which case minute crystals may be examined, or by means of the dichroscope when large crystals are available.

A **dichroscope** is simply a piece of Iceland spar set in a cylindrical frame that is provided with a small aperture at one end and either open or provided with a lens at the other end. Fig. 363 is a diagrammatic representation of the dichroscope. When held

up to the light the dichroscope shows two images of the aperture side by side, the diameter of the aperture being made such that the images do not overlap. If a pleochroic crystal is viewed through the dichroscope two colored images are seen simultaneously. The reason for this is that in a doubly refracting calcite crystal we have two sets of light waves vibrating in planes at right angles to each other.

The color of some crystals, as we have seen, varies with the direction, but by using a Nicol prism we may observe the two colors successively, one when the vibration plane of the nicol is parallel to the length of the crystal, and one when perpendicular to the length of the crystal. These colors are called **axial colors**.

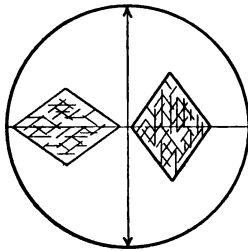


FIG. 364.—Calcite.

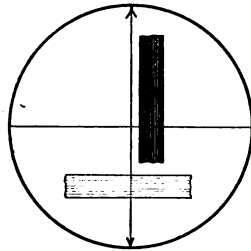


FIG. 365.—Biotite.

In uniaxial crystals there are two axial colors, hence the term **dichroic**. In biaxial crystals there are three axial colors, hence the term **trichroic**.

In order to determine the axial colors for particular directions it is necessary to ascertain the vibration plane of the lower nicol. For this purpose a rock-section containing biotite may be used. Biotite sections showing cleavage have very strong absorption. On revolving the section the biotite becomes very dark every  $180^\circ$ . The cross-wire which is parallel to the length of the biotite when it is darkest represents the vibration plane of the lower nicol as illustrated in Fig. 365, the arrow indicating this direction.

If a rock-section containing biotite is not available the test may be made by examining minute cleavage fragments of calcite obtained by pounding to a coarse powder, any kind of calcite. If mounted in oil of cloves or Canada balsam, the calcite rhombs have a marked relief when their long diagonals are parallel to the vibration plane of the lower nicol, but slight relief when their short diagonals are parallel to this direction as represented in Fig. 364. The vibration direction of the lower nicol is indicated by the arrow.

The trichroism of a biaxial crystal is beautifully illustrated by the soda amphibole, glaucophane, as seen in thin rock-sections

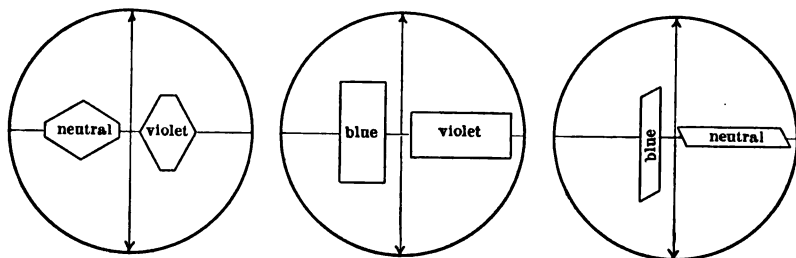


FIG. 366.

FIG. 367.

FIG. 368.

FIGS. 366-368.—Pleochroism of glaucophane.

under the microscope. Three kinds of cross-sections may be distinguished as follows: pseudo-hexagonal (Fig. 366), stout rectangular (Fig. 367), and thin with oblique ends (Fig. 368). These sections are respectively almost perpendicular to the  $c$ ,  $b$ , and  $a$  axes. These sections when rotated on the stage of the microscope show respectively the following pairs of colors: neutral and violet, blue and violet, blue and neutral. It will be seen that the color for the  $a$ -axis is the neutral tint for the mineral has this color when the  $a$ -axis is parallel to the vibration plane of the nicol (represented by the arrow). Similarly the violet is the color for the  $b$ -axis and blue for the  $c$ -axis. The three axial colors may be combined in an axial cross (Fig. 369).

In glaucophane it has been found that  $b = \beta$  and  $a$  (almost)  $= \alpha$  and  $c$  (almost)  $= \gamma$ . The absorption may be indicated by the following:  $\gamma > \beta > \alpha$ . This is called the **absorption scheme** and means that more light is absorbed in the  $\gamma$  or  $c$ -direction than in the  $\beta$  or  $b$ -direction and more in the  $\beta$  or  $b$ -direction than in the  $\alpha$  or  $a$ -direction. Sometimes Gothic letters are used instead of  $\alpha$ ,  $\beta$ , and  $\gamma$ .

#### 14. DISPERSION

By **dispersion** is meant the divergence in value or in position of the optical constants for different colors of the spectrum.

For isometric crystals we have simply dispersion for the indices of refraction. The index of refraction for the violet end of the spectrum is greater than that for the red end of the spectrum as indicated in Fig. 312, page 116. For diamond the dispersion is very large  $n_v - n_r = 0.063$ , hence the "fire" of the diamond. For fluorite the dispersion is very small  $n_v - n_r = 0.006$  hence fluorite is sometimes employed in making achromatic microscope lenses.

For uniaxial crystals we have different values of the indices of refraction  $n_\alpha$  and  $n_\gamma$  for different parts of the spectrum. For some crystals one part of the spectrum will give a positive interference-figure and another part a negative figure, while for an intermediate color of the spectrum the mineral will be isotropic.

In biaxial crystals there is more variety in the dispersion, not only varying values for  $n_\alpha$ ,  $n_\beta$ , and  $n_\gamma$ , but also variation in the position of the optic axes and axial plane and in the size of the axial angle.

In the orthorhombic system there can be no dispersion of the axial plane or of the bisectrices, as  $\alpha$ ,  $\beta$ , and  $\gamma$  always coincide with

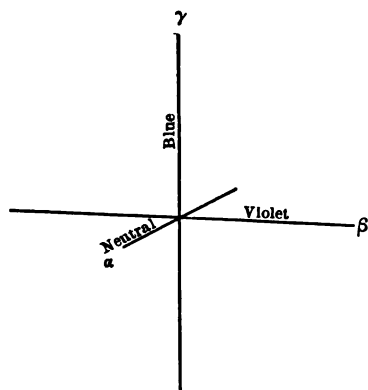


FIG. 369.—Axial colors of glaucophane.

the crystallographic axes. The color distribution is then symmetrical with respect to the axial plane and also a line normal to it. This is shown diagrammatically in Fig. 370, the dotted circles and hyperbolæ representing the blue part of the spectrum, say, while the full circles and hyperbolæ represent the red part of the spectrum. This is known as **symmetrical dispersion**.

In the monoclinic system the only fixed relation is that the  $b$ -axis is always either  $\alpha$ ,  $\beta$ , or  $\gamma$ . Hence the axial plane is either parallel or perpendicular to the (010) face. If the axial plane is perpendicular to (010), the position of the axial plane will vary for the different colors. If the  $b$ -axis is the acute bisectrix we have

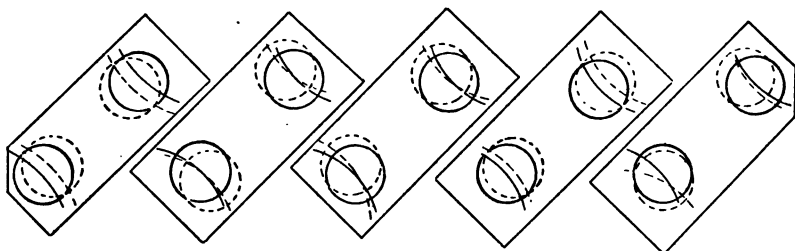


FIG. 370.  
Symmetrical  
dispersion.

FIG. 371.  
Crossed dis-  
persion.

FIG. 372.  
Horizontal  
dispersion.

FIG. 373.  
Inclined  
dispersion.

FIG. 374.  
Asymmetric  
dispersion.

the color of the interference figure symmetrical to the center of the figure as in Fig. 371. This is called **crossed dispersion**. If the  $b$ -axis is the obtuse bisectrix, then the color distribution of the interference figure of a section perpendicular to the acute bisectrix will be symmetrical to a line perpendicular to the axial plane as shown in Fig. 372. This is called **horizontal dispersion**. There is a third case in which the axial plane is parallel to the 010 face and the  $b$ -axis coincides with  $\beta$ . A section normal to the acute bisectrix will give an interference figure with color symmetrical to the trace of the axial plane as in Fig. 373. This is called **inclined dispersion**.

In the triclinic system there is both dispersion of the axial

plane, optic axes, and axial angles and no necessary connection between  $a, b, c$  and  $\alpha, \beta, \gamma$ . The interference figure has no color symmetry and for this reason it is called **asymmetric dispersion** (Fig. 374).

To make these observations it is necessary to use rather thick sections in a polariscope. Although these various kinds of dispersions are theoretically possible in the orthorhombic, monoclinic, and triclinic systems, they are not marked enough in most crystals to be observed. For good, though perhaps exaggerated, illustrations of these various kinds of dispersion see plate II in Tschermak's *Lehrbuch der Mineralogie*, 6th edition (1905).

## 15. ROTARY POLARIZATION

If a thick (1 mm. or more) basal section of a quartz crystal is examined in monochromatic light with crossed nicols it is found that, instead of being dark as most uniaxial crystals are, some light will be transmitted, but on rotating one nicol through a certain angle, depending upon the thickness and the kind of light, the field will become dark. Thus quartz has the curious property of **rotating the plane of polarization**. For a section of quartz 1 mm. thick, using red light the angle of rotation is  $13^\circ$ . For cinnabar, the only other mineral known to possess this property, the angle of rotation is  $325^\circ$  under similar conditions. As the angle of rotation depends upon the wave length of light used, in white light the section is never dark, but on rotation successive colors appear. In convergent light the interference figure is like the normal uniaxial figure except there is a light circular area at the center.

A substance that rotates the plane of polarization is said to be **optically active**. Besides the minerals quartz and cinnabar, this property is possessed by many artificially prepared crystals such as sodium chlorate, sodium periodate, strychnine sulfate, etc., and also by solutions of cane-sugar, tartaric acid, and many other organic compounds with asymmetric carbon atoms. In solutions



the angle of rotation depends upon the amount of substance in solution. Sugar analysis is based upon this fact. The sugar solution, the strength of which is to be determined, is placed in a tube between the crossed nicols of an instrument called the **polarimeter**, the nicols being horizontal and one of them capable of being rotated. The amount of rotation necessary to produce darkness determines the strength of the solution.

Both in crystals and in solutions the rotation may be right-handed (clock-wise) or left-handed (counter-clock-wise). There

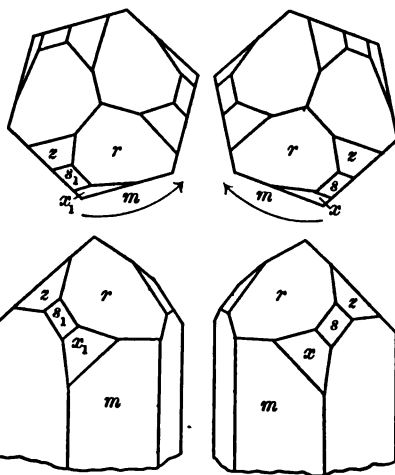


FIG. 375.

FIG. 376.

Enantiomorphous quartz crystals.

seems to be a curious connection between the crystal form and the optical activity. Quartz crystallizes in the trigonal-trapezohedral class of the hexagonal system. Occasional crystals are found with small faces of the trigonal trapezohedron  $x\{51\bar{6}1\}$  to the right and above  $m\{10\bar{1}0\}$ . These crystals are called right-handed and one is illustrated by Fig. 376. Other crystals have faces of the complementary form,  $x_1\{61\bar{5}1\}$ , a face to the left and above  $m\{10\bar{1}0\}$ . These, in contrast, are known as left-handed

(see Fig. 375). The two crystals figured are exactly alike in shape, yet one cannot be derived from the other by any possible rotation. They bear the same relation to each other that the right and left hands do, one being the mirror-image of the other. Such crystals are said to be **enantiomorphous**.<sup>1</sup> Basal sections cut from a right-handed quartz crystal rotate the plane of polarization to the right and similar sections from a left-handed crystal rotate the plane of polarization to the left.

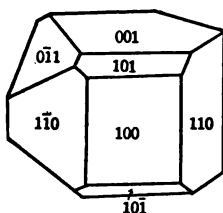


FIG. 377.

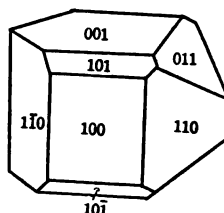


FIG. 378.

Enantiomorphous tartaric acid crystals.

The two modifications of tartaric acid,  $C_4H_6O_6$ , (dextro- and lævo-) each crystallize in the monoclinic sphenoidal class in exactly similar but enantiomorphous forms. While *d*-tartaric acid possesses the sphenoid  $\{011\}$  at the positive end of the *b*-axis (Fig. 377), *l*-tartaric acid possesses a corresponding sphenoid  $\{0\bar{1}1\}$  at the negative end of the *b*-axis (Fig. 378). Now solutions of *d*-tartaric acid rotate the plane of polarization to the right and solutions of *l*-tartaric acid to the left. This important relation was discovered by Pasteur. The difference between these two compounds is believed to be due to the space arrangement of the atoms, assuming an asymmetric carbon atom. From such considerations is built up the science of stereochemistry.

<sup>1</sup>In Figs. 375 and 376, also 377 and 378, the left-handed crystals are drawn as if the axes had been rotated to the right instead of to the left, as ordinarily. This brings out the enantiomorphous relation better. The left-handed crystal may be drawn by tracing the drawing of the right-handed crystal through the back of the drawing, thus reversing it.

Racemic acid is identical in composition and chemical properties with the other two forms of tartaric acid, but in solution is optically inactive. From a solution of racemic acid, equal quantities of *d*-tartaric and *l*-tartaric acid crystallize out. There are a number of such **racemic compounds**, as they are called. All of these facts in regard to optical activity have an important bearing upon the theory of crystal structure.

## 16. OPTICAL ANOMALIES

Among the optical properties of crystals there are many anomalies. Certain isometric crystals are doubly refracting and some uniaxial crystals give a biaxial interference figure with a small axial angle. There are also anomalies in extinction, in interference colors, and in interference figures.

Among isometric minerals only a comparatively few, such as spinel and cuprite, are always normal. Sections of many isometric crystals show double refraction either in the section as a whole or in certain parts. Fig. 379 represents an octahedral section of garnet, a mineral which often exhibits optical anomalies in thick sections. This section in polarized light consists of a triangular isotropic area bounded by three doubly refractive sectors, each of which extinguishes parallel to

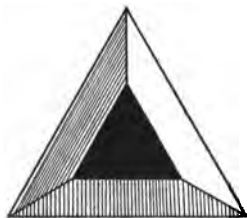


FIG. 379.—Garnet.

and normal to the triangular outline.

Sections of leucite, an isometric rock-forming mineral common in the lavas of central Italy, often show very weak double refraction and fine polysynthetic twinning lamellæ.

Little spherical portions of the hyalite variety of opal, one of the very few amorphous minerals, often show a dark cross between crossed nicols which is due to the extinction of a doubly refracting substance.

Basal sections of some crystals of apatite, beryl, and vesuvia-

nite, all uniaxial minerals, exhibit in convergent polarized light biaxial interference figures with small axial angles.

Most of these anomalies are due to molecular strain developed by sudden cooling, rapid growth, pressure of surrounding rocks, etc. There are experimental proofs for all these cases. Thus, double refraction can be produced in glass, an amorphous substance, by subjecting it to pressure in a vise.

In the case of leucite the anomaly may be explained by dimorphism. On heating a leucite crystal to about  $433^{\circ}$  C. it becomes isotropic. Hence the compound,  $\text{KAl}(\text{SiO}_3)_2$ , is dimorphous. Above  $433^{\circ}$  C. it is isometric, while below that temperature it is biaxial with weak double refraction. On crystallizing from fusion in an igneous rock it assumed an isometric form, the trapezohedron, which it retained on cooling to the ordinary temperature, while it changed from an isotropic substance to an anisotropic substance.

The Berlin blue interference color is the best example of an anomalous interference color. This is a deep blue of the first order which cannot be found on the color chart, for it is between the black and the white of the first order. It is characteristic of chlorite and zoisite and is due to the fact that the axial angle for these minerals varies considerably for different colors of the spectrum. As the axial angle for yellow light is nearly  $0^{\circ}$ , the resultant color, leaving out the yellow, is blue.

In some uniaxial minerals, such as vesuvianite, the crystal may be optically positive for a certain color and optically negative for another color, while for some intermediate color it is isotropic and hence the interference color in white light is the result of all the colors of the spectrum except that color.

Crystals with strong dispersion of the optic axes such as titanite ( $2E_r = 54^{\circ}$ ;  $2E_v = 33^{\circ}$ ) will not give complete extinction in white light. The interference figure will be abnormal in that the hyperbolæ are colored instead of black.

## 17. OPTICAL ORIENTATION

By this term is meant the position of  $\alpha$ ,  $\beta$ ,  $\gamma$ , the acute bisectrix, and the axial plane of the optical indicatrix with reference to the crystallographic axes.

In uniaxial crystals there are but two possible orientations: (1)  $c$  coincides with  $\gamma$  (positive crystals), (2)  $c$  coincides with  $\alpha$  (negative crystals). The tests for optical character have been mentioned in Section 11.

In orthorhombic crystals the three directions  $\alpha$ ,  $\beta$ , and  $\gamma$  must coincide with the crystallographic axes as there is parallel extinction on (100), (010), and (001). The axial plane is always a plane of symmetry. There are the following six possibilities in the orientation  $\alpha\beta\gamma$ ,  $\alpha\gamma\beta$ ,  $\beta\alpha\gamma$ ,  $\beta\gamma\alpha$ ,  $\gamma\alpha\beta$ ,  $\gamma\beta\alpha$ , the order being  $a$ ,  $b$ ,  $c$  in each case. There are two ways of determining the orientation, one by testing for the faster and slower rays in various sections, the other by obtaining the interference figure. The first case is illustrated by Fig. 380 ( $a$ ,  $b$ ,  $c$ ), which represents sections parallel to (100), (010) and (001). The faster and slower ray is determined for each of the section and marked by the letters  $f$  and  $s$ . As the  $c$ -axis is the slower in two sections it must be  $\gamma$ . The (001)

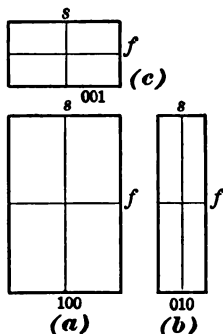


FIG. 380.  
Optical orientation.

section containing  $a$  and  $b$  must contain  $\alpha$  and  $\beta$ . Of these  $a$  is the slower, hence it is  $\beta$ . So we have the orientation  $a = \beta$ ,  $b = \alpha$ ,  $c = \gamma$  or  $\beta\alpha\gamma$ .

Fig. 381 represents a basal section of topaz (topaz has a good cleavage parallel to (001), so chips are easily prepared) bounded by faces of (110) and (120). The interference figure lies across the short diagonal or in the direction of the  $a$ -axis as represented conventionally in the figure. Now the plane of the optic axes contains  $\alpha$  and  $\gamma$ , so that in this case  $b = \beta$ . By determining the

faster and slower ray in this section we find that the short diagonal is the faster ray. We know that  $\alpha$ , and not  $\gamma$ , is faster than  $\beta$ , so that we have  $a = \alpha$ ,  $b = \beta$ ,  $c = \gamma$ . Or if the optical character be determined it is found to be positive so that  $\gamma$ , the acute bisectrix, coincides with  $c$ .

Another example is Fig. 382, representing a basal cleavage of muscovite. The interference figure lies along the  $b$ -axis so that the  $a$ -axis is  $\beta$ . The  $b$ -axis is then either  $\alpha$  or  $\gamma$ . By testing it is found to be the slower ray. So we have the orientation  $a = \beta$ ,  $b = \gamma$ ,  $c = \alpha$ . The optical character is negative so that  $c$ , the

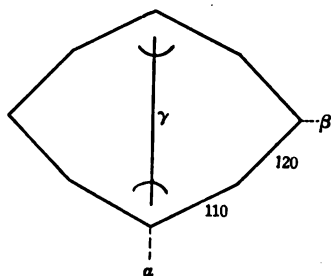


FIG. 381.—Topaz.

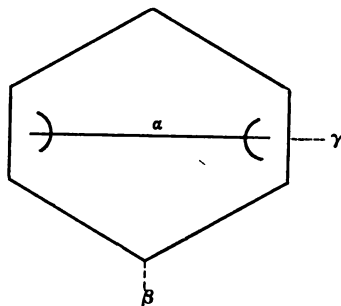


FIG. 382.—Muscovite.

acute bisectrix, is  $\alpha$ . In reality muscovite is monoclinic and  $\alpha$  makes a small angle ( $1^{\circ} 30'$ ) with the  $c$ -axis, but this may be disregarded.

In monoclinic crystals the crystallographic axis  $b$  always coincides with either  $\alpha$ ,  $\beta$ , or  $\gamma$ . The other two are in the plane of the  $a$  and  $c$  axes, but make variable angles with these axes. These angles are the extinction angles on (010), the extinction on (100) and (001) being either parallel or symmetrical. The axial plane in the monoclinic system is either parallel to, or normal to (010), the plane of symmetry.

In triclinic crystals none of the indicatrix axes coincide with the crystallographic axes and consequently the extinction on all faces is oblique. It is difficult to determine the optical orientation of a triclinic crystal.

## 18. THE OPTICAL CONSTANTS AND THEIR DETERMINATION

The optical constants differ for the various crystal systems. The only optical constant for isometric crystals is the index of refraction, which varies with the kind of light used. Thus for diamond  $n_{\text{Li}}=2.408$ ;  $n_{\text{Na}}=2.417$ ;  $n_{\text{Tl}}=2.425$ , the subscripts referring to the fact that lithium, sodium, and thallium salts were used for producing monochromatic light.

In uniaxial crystals there is the optical character (positive or negative), two indices of refraction  $n_\alpha$  and  $n_\gamma$  for various kinds of monochromatic light, the double refraction,  $n_\gamma - n_\alpha$ , and if the crystal is colored the axial colors for  $\alpha$  and  $\gamma$ , and the absorption  $\alpha > \gamma$  or  $\gamma > \alpha$ . It is to be noted that the optical constants for tetragonal and hexagonal crystals are exactly the same. Crystals of these two systems can only be distinguished by outline, by cleavage, or by etching-tests.

For orthorhombic crystals we have the orientation, the optical character (positive or negative), three indices of refraction,  $n_\alpha$ ,  $n_\beta$ , and  $n_\gamma$ , the double refraction  $n_\gamma - n_\alpha$ , and the axial angle  $2V$ , all of these for various kinds of monochromatic light. We also have, if the mineral is colored, the axial colors for  $\alpha$ ,  $\beta$ , and  $\gamma$  and the absorption scheme  $\alpha \geq \beta \geq \gamma$ .

For monoclinic crystals we have all the optical constants for the orthorhombic system in addition to the extinction angles  $\gamma \wedge c$ ,  $\beta \wedge c$ , or  $\alpha \wedge c$ , and the position of the axial plane.

For triclinic crystals we have, in addition to the constants for the orthorhombic system, the position of the principal optical sections, which planes contain  $\alpha$  and  $\beta$ ,  $\beta$  and  $\gamma$ , and  $\alpha$  and  $\gamma$ .

It will be seen that the principal quantitative optical determinations are index of refraction and axial angle. Accurate determinations of these as well as of extinction angles must be made in monochromatic light.

One method for determining the index of refraction is called the prism method. The crystal cut in the form of a prism of about  $60^\circ$  is mounted on a reflection goniometer or spectrometer. Light

from the collimator is refracted both on entering and emerging from the prism as shown in Fig. 384. The angle of deviation,  $d$ , is a minimum for a particular position of the prism which is found by trial. Then  $n = \frac{\sin \frac{1}{2}(d + p)}{\sin \frac{1}{2}p}$  where  $d$  is the angle of deviation and  $p$ , the internal angle of the prism.

In isometric crystals a prism cut in any direction gives but one value of the index of refraction, while in uniaxial crystals a prism with refracting edge parallel to the  $c$ -axis gives two values  $n_a$  and  $n_r$ . In biaxial crystals it is necessary to have two prisms to obtain the three values  $n_a$ ,  $n_b$ , and  $n_r$ .

Another method for determining the index of refraction depends upon total reflection and may be illustrated by the dia-

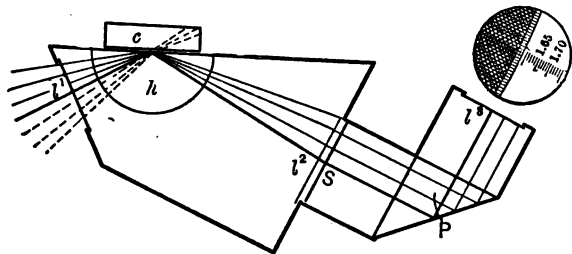


FIG. 383.—The Smith refractometer.

grammatic cross-section of the Smith refractometer of Fig. 383. It consists of a metal frame holding a hemisphere,  $h$ , of highly refracting glass ( $n = 1.79$ ), a totally-reflecting prism,  $P$ , and lenses at  $l^1$ ,  $l^2$ , and  $l^3$ . The substance, the index of refraction of which is sought, is placed over the glass-hemisphere at  $c$  and in close contact with it by means of a drop of  $\alpha$ -monobromnaphthalene or methylene iodid. As the glass hemisphere has a greater index of refraction than the substance (this is a necessary condition), rays of light entering at  $l^1$  are in part totally reflected back into the hemisphere, the rays represented by the dotted lines entering the substance. The totally reflected rays fall on a scale  $S$ , engraved on glass and are reflected by the prism  $P$  into the eye-piece at  $l^3$ .



The field of vision appears as in the circle above the eye-piece, one-half being light and the other half dark. After the instrument has been calibrated the index of refraction may be read off directly on the scale. The reading in the figure indicates a doubly refracting substance with indices of refraction of 1.583 and 1.607. Accurate observations should be made in monochromatic light, but examination in white light will indicate the amount of dispersion.

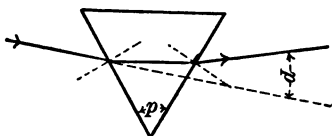


FIG. 384.

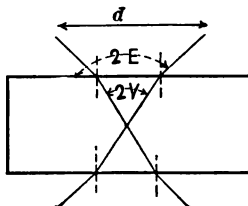


FIG. 385.

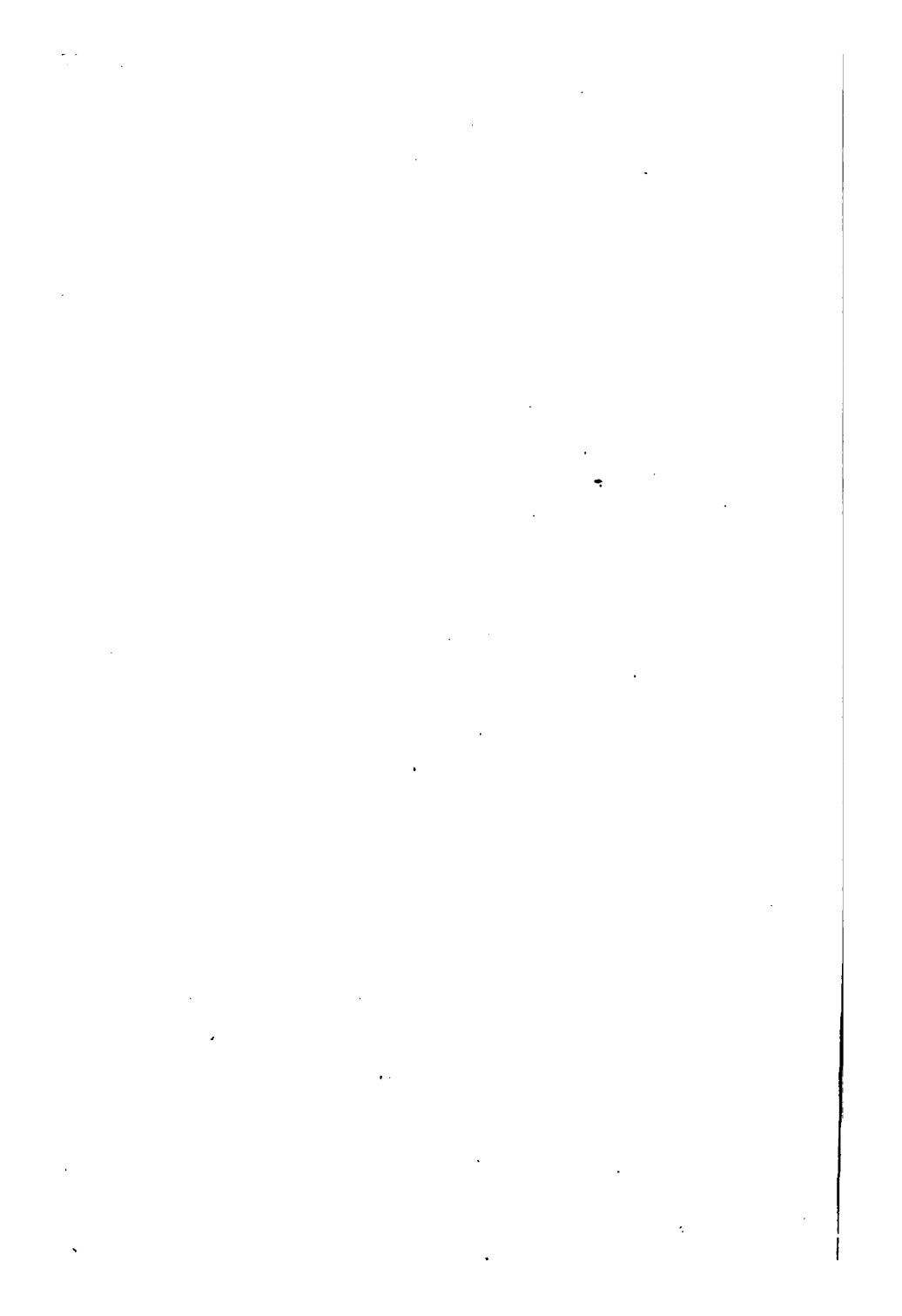
The axial angle of a biaxial crystal may be measured by means of an axial angle apparatus which is practically a reflection goniometer plus Nicol prisms. If a suitable crystal is mounted, so that it can be rotated around its  $\beta$  direction as an axis, between horizontal crossed nicols, so arranged that the interference figure shows an hyperbola, the apparent axial angle can be determined by reading the circle when the vertices of the hyperbola are tangent to the cross-wires. Fig. 385 represents a section of a biaxial parallel to the axial plane. It will be seen that the angle measured is not  $2V$ , but another angle which is called  $2E$  and related to it by the following equation,  $\sin E = \beta \sin V$ ,  $\beta$  being the index of refraction in the direction of the optic axis. The value  $2E$  is very often recorded as it is obtained directly.

Another less accurate method of measuring the axial angle is based upon the fact that the distance apart of the vertices ( $d$  in Fig. 385). of the hyperbola of an interference figure is proportional to the value of  $2E$ . This determination may be made by using a micrometer eye-piece. The distance apart of the branches of the hyperbola of a substance with previously determined value of  $2E$  is measured. This determines the constant  $C$  in the

equation  $\sin E = d \div C$ . So for other crystals using the same microscope and combination of lenses the value  $E$  may be calculated from the measurement of  $d$  and substitution of  $C$ .

### Synopsis of the Optical Properties and Constants for the Crystal Systems

ISOTROPIC	Indicatrix a sphere	ISOMETRIC	All sections remain dark	$n$	No interference figure		
	UNIAxIAL Indicatrix a spheroid of revolution	TETRAGONAL	Basal section dark. Parallel extinction in most sections.	$n_\alpha, n_\gamma$	Interference figure with dark cross and colored circles.		
ANISOTROPIC	HEXAGONAL	Basal sections dark. Parallel extinction in most sections	$n_\alpha, n_\gamma$	Interference figure with dark cross and colored circles.			
	ORTHORHOMBIC.	Parallel extinction in most sections.	$n_\alpha, n_\beta, n_\gamma$	Interference figure with dark hyperbola and colored ellipses and lemniscates.	Symmetrical dispersion.	2V	
	MONOCLINIC	Parallel extinction in 100, 001, and $h0l$ sections. Oblique in others.	$n_\alpha, n_\beta, n_\gamma$	Interference figure with dark hyperbola and colored ellipses and lemniscates.	Horizontal, inclined, or crossed dispersion.	2V	
	BIAXIAL Indicatrix a triaxial ellipsoid	TRICLINIC	Oblique extinction in all sections.	$n_\alpha, n_\beta, n_\gamma$	Interference figure with dark hyperbola and colored ellipses and lemniscates.	Asymmetric dispersion.	2V



## PART IV

### THE CHEMICAL PROPERTIES OF MINERALS

#### 1. INTRODUCTORY

As minerals are natural substances of definite chemical composition it is necessary for the student to have a knowledge of chemistry before he can intelligently study mineralogy, much less determine minerals. The commonly accepted classification of minerals is primarily a chemical one and while a few simple physical tests often serve to identify a mineral, a more or less complete chemical analysis is frequently necessary.

On the other hand, the student may derive much chemical knowledge from a study of minerals. The compounds of such elements as titanium, molybdenum, tungsten, and vanadium are perhaps best studied in minerals.

With the exception of some inert gases of the atmosphere (argon, krypton, neon, and xenon) all of the eighty-two known elements occur in minerals. Some are exceedingly rare and confined to one or two minerals, while others are very common and widely distributed in minerals. The following table of the elements with their symbols and atomic weights shows to some extent their occurrence in minerals.

Table of Elements with their Atomic Weights  
(International Committee, 1912)

Element	Symbol	Atomic weight	Occurrence
Aluminum.....	Al	27.1	Corundum, $Al_2O_3$
Antimony.....	Sb	120.2	Stibnite, $Sb_2S_3$
Argon.....	A	39.9	In the atmosphere
Arsenic.....	As	74.9	Arsenopyrite, $FeAsS$
Barium.....	Ba	137.4	Barite, $BaSO_4$
Beryllium.....	Be	9.1	Beryl, $Be_3Al_2(SiO_3)_6$
Bismuth.....	Bi	208.0	Bismuthinite, $Bi_2S_3$
Boron.....	B	11.0	Colemanite, $Ca_2B_6O_{11} \cdot 5H_2O$
Bromin.....	Br	79.9	Bromyrite, $AgBr$
Cadmium.....	Cd	112.4	Greenockite, $CdS$
Caesium.....	Cs	132.8	Pollucite, $H_2Cs_2Al_2(SiO_3)_4$
Calcium.....	Ca	40.1	Calcite, $CaCO_3$
Carbon.....	C	12.0	Graphite, C
Cerium.....	Ce	140.2	Monazite, $(CeLa)PO_4$
Chlorin.....	Cl	35.5	Halite, $NaCl$
Chromium.....	Cr	52.0	Chromite, $FeCr_2O_4$
Cobalt.....	Co	59.0	Smaltite, $(Co,Ni)As_2$
Copper.....	Cu	63.6	Chalcopyrite, $CuFeS_2$
Dysprosium.....	Dy	162.5	With the rare earths
Erbium.....	Er	167.7	Sipylite, $ErNbO_4$
Europium.....	Eu	152.0	With the rare earths
Fluorin.....	F	19.0	Fluorite, $CaF_2$
Gadolinium.....	Gd	157.3	In gadolinite
Gallium.....	Ga	69.9	In sphalerite
Germanium.....	Ge	72.5	Argyrodite, $Ag_8GeS_6$
Gold.....	Au	197.2	Gold Au
Helium.....	He	4.0	In uraninite
Hydrogen.....	H	1.0	Water, $H_2O$
Indium.....	In	114.8	In sphalerite
Iodin.....	I	126.9	Iodyrite, $AgI$
Iridium.....	Ir	193.1	Iridosmine, $(Ir,Os)$
Iron.....	Fe	55.8	Hematite, $Fe_2O_3$
Krypton.....	Kr	82.9	In the atmosphere
Lanthanum.....	La	139.0	Lanthanite, $La_2(CO_3)_2 \cdot 9H_2O$
Lead.....	Pb	207.1	Galena, $PbS$
Lithium.....	Li	6.9	Lepidolite, $K,Li,Al$ silicate
Lutecium.....	Lu	174.0	With the rare earths
Magnesium.....	Mg	24.3	Magnesite, $MgCO_3$
Manganese.....	Mn	54.9	Pyrolusite, $MnO_2$
Mercury.....	Hg	200.6	Cinnabar, $HgS$
Molybdenum.....	Mo	96.0	Molybdenite, $MoS_2$
Neodymium.....	Nd	144.3	In monazite



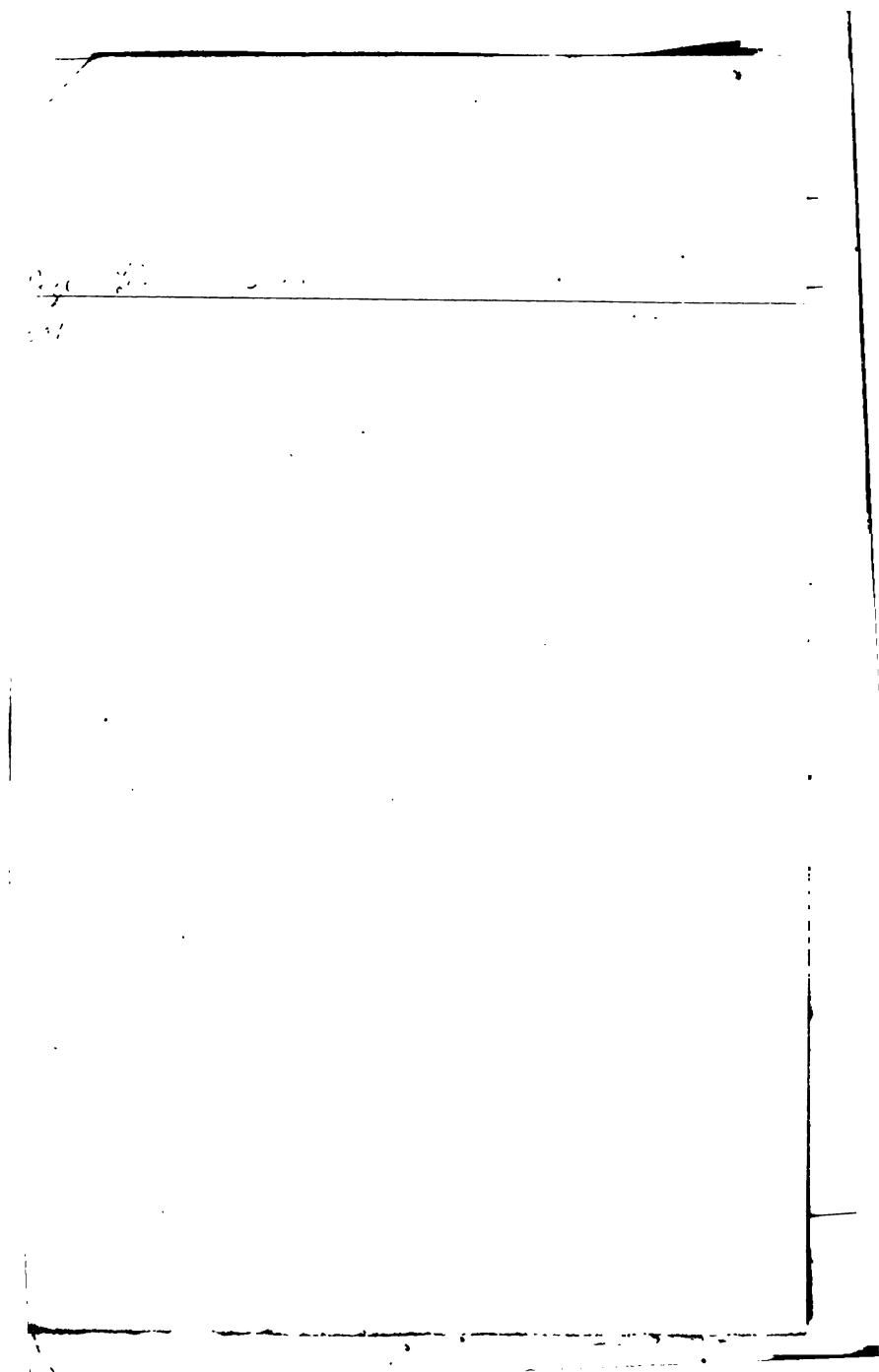


Table of Elements with their Atomic Weights—Continued

Element	Symbol	Atomic weight	Occurrence
Neon.....	Ne	20.2	In the atmosphere
Nickel.....	Ni	58.7	Millerite, NiS
Niobium.....	Nb	93.5	Columbite, (FeMn)(NbO <sub>3</sub> ) <sub>2</sub>
Niton.....	Nt	222.4	Radium emanation
Nitrogen.....	N	14.0	Soda Niter, NaNO <sub>3</sub>
Osmium.....	Os	190.9	Iridosmine, (Ir,Os)
Oxygen.....	O	16.0	Water, H <sub>2</sub> O
Palladium.....	Pd	106.7	Palladium, Pd
Phosphorus.....	P	31.0	Apatite, Ca <sub>5</sub> F(PO <sub>4</sub> ) <sub>3</sub>
Platinum.....	Pt	195.2	Platinum, Pt
Potassium.....	K	39.1	Sylvite, KCl
Praseodymium.....	Pr	140.6	In monazite
Radium.....	R	226.4	In uraninite
Rhodium.....	Rh	102.9	In platinum
Rubidium.....	Rb	85.4	In rhodizite
Ruthenium.....	Ru	101.7	Laurite, RuS <sub>2</sub>
Samarium.....	Sa	150.4	In samarskite
Scandium.....	Sc	44.1	In euxenite
Selenium.....	Se	79.2	Clausthalite, PbSe
Silicon.....	Si	28.3	Quartz, SiO <sub>2</sub>
Silver.....	Ag	107.9	Argentite, Ag <sub>2</sub> S
Sodium.....	Na	23.0	Halite, NaCl
Strontium.....	Sr	87.6	Celestite, SrSO <sub>4</sub>
Sulfur.....	S	32.1	Sulfur, S
Tantalum.....	Ta	181.5	Tantalite, Fe(TaO <sub>3</sub> ) <sub>2</sub>
Tellurium.....	Te	127.5	Calverite, AuTe <sub>2</sub>
Terbium.....	Tb	159.2	In gadolinite
Thallium.....	Tl	204.0	Lorandite, TlAsS <sub>2</sub>
Thorium.....	Th	232.4	Thorite, ThSiO <sub>4</sub>
Thulium.....	Tm	168.5	In gadolinite
Tin.....	Sn	119.0	Cassiterite, SnO <sub>2</sub>
Titanium.....	Ti	48.1	Rutile, TiO <sub>2</sub>
Tungsten.....	W	184.0	Wolframite, (Fe,Mn)WO <sub>4</sub>
Uranium.....	U	238.5	Uraninite, U <sub>3</sub> O <sub>8</sub>
Vanadium.....	V	51.0	Vanadinite, Pb <sub>3</sub> Cl(VO <sub>4</sub> ) <sub>3</sub>
Xenon.....	Xe	130.2	In the atmosphere
Ytterbium.....	Yb	172.0	In gadolinite
Yttrium.....	Y	89.0	Xenotime, YPO <sub>4</sub>
Zinc.....	Zn	65.4	Sphalerite, ZnS
Zirconium.....	Zr	90.6	Zircon, ZrSiO <sub>4</sub>



Of the eighty-two elements enumerated only about eighteen occur as minerals. They are carbon, sulfur, selenium, tellurium, arsenic, antimony, bismuth, mercury, copper, silver, gold, lead, iron, platinum, palladium, iridium, osmium, tantalum, and tin. This leaves out of consideration the free gases of the atmosphere. From a chemical standpoint the elements may be divided into two classes, the metals and the non-metals. The metals include such elements as copper, silver, gold, lead, iron, and platinum. Some of these occur as alloys, such as electrum (Au,Ag), amalgam (Ag,Hg), nickel-iron (Fe,Ni), and iridosmine (Ir,Os). The non-metals include such elements as oxygen, hydrogen, nitrogen, phosphorus, and sulfur. Arsenic, antimony, and bismuth are intermediate in their properties between metals and non-metals and are sometimes called semi-metals or metalloids.

## 2. CHEMICAL TYPES

Most minerals are, of course, chemical compounds, or combinations of two or more elements. These compounds are the chemical types recognized by chemists, namely, oxids, acids, bases, and salts with their various subdivisions.

**Acids** are compounds, the dilute water solutions of which contain hydrogen ions. According to the theory of ions it is the hydrogen ions that give the acid properties such as sour taste and the change of blue litmus to red. The strength of the acid depends upon the proportion of hydrogen ions present or upon the degree of dissociation. Hydrochloric and sulfuric acids are strong acids, while carbonic and silicic acids are weak acids. Acids are compounds of hydrogen with the halogens (Cl, Br, I, or F), with sulfur, or with certain radicals, such as  $\text{CO}_3$ ,  $\text{SO}_4$ ,  $\text{PO}_4$ ,  $\text{AsO}_4$ ,  $\text{AsS}_3$ ,  $\text{AsS}_4$ ,  $\text{SbS}_3$ ,  $\text{SbS}_4$ . These are called **acid radicals**. The most common acids are those containing oxygen and are known as oxygen acids or oxy-acids. The oxy-acids are monobasic ( $\text{HNO}_3$ ), dibasic ( $\text{H}_2\text{SO}_4$ ), tribasic ( $\text{H}_3\text{PO}_4$ ) or tetrabasic ( $\text{H}_4\text{SiO}_4$ ), according as they have one, two, three, or four replace-

able H atoms. The polybasic acids, as they are called, are capable of forming condensed acids by subtracting water. This is especially prominent with the silicic acids. Orthosilicic acid is  $\text{H}_4\text{SiO}_4$ ;  $\text{H}_4\text{SiO}_4 - \text{H}_2\text{O} = \text{H}_2\text{SiO}_3$ , metasilicic acid;  $2\text{H}_4\text{SiO}_4 - \text{H}_2\text{O} = \text{H}_6\text{Si}_2\text{O}_7$ , diorthosilicic acid;  $2\text{H}_4\text{SiO}_4 - 3\text{H}_2\text{O} = \text{H}_2\text{Si}_2\text{O}_5$ , dimetasilicic acid. There are also  $\text{H}_4\text{Si}_3\text{O}_8$  ( $3\text{H}_4\text{SiO}_4 - 4\text{H}_2\text{O}$ ) and  $\text{H}_8\text{Si}_5\text{O}_{10}$  ( $3\text{H}_4\text{SiO}_4 - 2\text{H}_2\text{O}$ ).

The replacement in the oxy-acids of O by S gives compounds called **sulfo-acids**. Thus  $\text{H}_3\text{AsO}_4$  is arsenic acid or oxy-arsenic acid, while  $\text{H}_3\text{AsS}_4$  is sulfarsenic acid.  $\text{H}_3\text{AsO}_3$  is arsenious acid, while  $\text{H}_3\text{AsS}_3$  is sulfarsenious acid. Various condensed acids may be derived from the above by the subtraction of  $\text{H}_2\text{S}$ , entirely analogous to the condensed oxy-acids. Thus we have  $\text{HAsS}_2$  ( $\text{H}_3\text{AsS}_3 - \text{H}_2\text{S}$ ), metasulfarsenious acid and  $\text{H}_4\text{As}_2\text{S}_7$  ( $2\text{H}_3\text{AsS}_4 - \text{H}_2\text{S}$ ), pyrosulfarsenic acid. Very few of these acids exist either as minerals or prepared compounds, but salts of all of them are known as minerals.

**Bases** are compounds the dilute water solutions of which contain hydroxyl (OH) ions. It is the hydroxyl ions that give the basic properties such as soapy feel, and the changes of red litmus to blue. The strength of the base is proportional to the number of hydroxyl ions present. The strong bases such as KOH and NaOH are called alkalis. Weak bases are represented by  $\text{Fe}(\text{OH})_3$  and  $\text{Al}(\text{OH})_3$ . Among the bases represented by minerals are  $\text{Mg}(\text{OH})_2$ ,  $\text{Mn}(\text{OH})_2$ ,  $\text{Al}(\text{OH})_3$ ,  $\text{AlO}_2\text{H}(\text{Al}(\text{OH})_3 - \text{H}_2\text{O})$ ,  $\text{FeO}_2\text{H}(\text{Fe}(\text{OH})_3 - \text{H}_2\text{O})$ , and  $\text{Fe}_4\text{O}_6\text{H}_9$  ( $4\text{Fe}(\text{OH})_3 - 3\text{H}_2\text{O}$ ).

**Oxids** are compounds of the elements with oxygen. Elements, the oxids of which form bases with water, are called metals. These oxids are called **basic anhydrids** for this reason. Elements, the oxids of which form acids with water, are called non-metals. These oxids are called **acid anhydrids**.

**Salts** are compounds formed by the union of bases with acids, the metal of the base uniting with the non-metal or acid radical of the acid to form the salt, while the hydroxyl of the base unites with the hydrogen of the acid to form water thus,  $\text{NaOH} + \text{HCl}$

$=\text{NaCl}+\text{H}_2\text{O}$ . In dilute solutions salts are dissociated into two parts or ions as they are called. The metal is one ion, and is called the cation, while the non-metal or acid radical is the other ion, and is called the anion.

Among salts we may distinguish halogen salts, oxy-salts, and sulfo-salts corresponding to the acids of which they are the derivatives. The following represent **salts found as minerals**: Sulfid,  $\text{PbS}$ ; selenid,  $\text{PbSe}$ ; tellurid,  $\text{PbTe}$ ; arsenid,  $\text{FeAs}_2$ ; antimonid,  $\text{Ag}_3\text{Sb}$ ; sulfarsenite,  $\text{Ag}_3\text{AsS}_3$ ; sulfarsenate,  $\text{Cu}_3\text{AsS}_4$ ; sulfantimonite,  $\text{Ag}_3\text{SbS}_3$ ; sulfantimonate,  $\text{Cu}_3\text{SbS}_4$ ; sulfoferrite,  $\text{CuFeS}_2$ ; sulfochromite,  $\text{FeCr}_2\text{S}_4$ ; sulfovanadate,  $\text{Cu}_3\text{VS}_4$ ; sulfo-germanate,  $\text{Ag}_3\text{GeS}_4$ ; sulfostannite,  $\text{PbSnS}_2$ ; chlorid,  $\text{AgCl}$ ; bromid,  $\text{AgBr}$ ; iodid,  $\text{AgI}$ ; fluorid,  $\text{CaF}_2$ ; fluosilicate,  $\text{K}_2\text{SiF}_6$ ; carbonate,  $\text{CaCO}_3$ ; meta-aluminate,  $\text{MgAl}_2\text{O}_4$ ; metaferrite,  $\text{FeFe}_2\text{O}_4$ ; meta-chromite,  $\text{FeCr}_2\text{O}_4$ ; ehromate,  $\text{PbCrO}_4$ ; metaniobate,  $\text{Fe}(\text{NbO}_3)_2$ ; metatantalate,  $\text{Fe}(\text{TaO}_3)_2$ ; phosphate,  $\text{LiFePO}_4$ ; arsenate,  $\text{FeAsO}_4\cdot\text{H}_2\text{O}$ ; vanadate,  $\text{BiVO}_4$ ; antimonate,  $\text{Ca}_2\text{Sb}_2\text{O}_7$ ; nitrate,  $\text{NaNO}_3$ ; borate,  $\text{AlBO}_3$ ; sulfate,  $\text{BaSO}_4$ ; ehromate,  $\text{PbCrO}_4$ ; selenite,  $\text{CuSeO}_3\cdot 2\text{H}_2\text{O}$ ; tellurite,  $\text{Fe}(\text{TeO}_3)_3\cdot 4\text{H}_2\text{O}$ ; tungstate,  $\text{CaWO}_4$ ; molybdate,  $\text{PbMoO}_4$ ; metatitanate,  $\text{CaTiO}_3$ ; orthosilicate,  $(\text{Mg},\text{Fe})_2\text{SiO}_4$ ; metasilicate,  $\text{CaSiO}_3$ ; trisilicate,  $\text{KAlSi}_3\text{O}_8$ ; dimetasilicate,  $\text{LiAl}(\text{Si}_2\text{O}_6)_2$ ; diorthosilicate,  $\text{Pb}_3\text{Si}_2\text{O}_7$ .

All the above are normal salts, that is, all the hydrogen of the acid or hydroxyl of the base has been replaced by metals or by acid radicals respectively. A compound in which only part of the hydrogen of the acid has been replaced by a metal is called an **acid salt**. Among minerals we have  $\text{KHSO}_4$ , and  $\text{H}_2\text{CuSiO}_4$ , which are called acid potassium sulfate, and acid copper silicate respectively. A compound in which only part of the hydroxyl of the base is replaced by an acid radical is called a **basic salt**. Among minerals we have  $\text{Cu}_2(\text{OH})_2\text{CO}_3$ ,  $\text{Cu}_4(\text{OH})_6\text{Cl}_2$ ,  $\text{Cu}_2(\text{OH})\text{AsO}_4$ , and many others. These three minerals are called basic copper carbonate, chlorid, and arsenate respectively.

The formulæ of some minerals are written as if they consist of two or more separate molecules. These are called **molecular**

**compounds** for want of a better name. Among molecular compounds are double salts and hydrates or hydrous salts. **Double salts** are (1) salts composed of two metals with a common acid radical (example, dolomite  $\text{CaCO}_3 \cdot \text{MgCO}_3$ ), (2) salts of a single metal with two distinct acid radicals (example, arsenopyrite  $\text{FeS}_2 \cdot \text{FeAs}_2$ ) or (3) salts in which both the metal and acid radical are different (example, kainite  $\text{MgSO}_4 \cdot \text{KCl} \cdot 3\text{H}_2\text{O}$ ).

Acid and basic salts may also be written in the form of double salts.  $\text{KHSO}_4 = \text{K}_2\text{SO}_4 \cdot \text{H}_2\text{SO}_4$ ,  $\text{Cu}_2(\text{OH})_2\text{CO}_3 = \text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$ . Another kind of compound is  $\text{Sb}_2\text{S}_2\text{O}$ , antimony oxy-sulfid, which may be written  $2\text{Sb}_2\text{S}_3 \cdot \text{Sb}_2\text{O}_3 (3\text{Sb}_2\text{S}_2\text{O})$ . Similarly  $\text{Pb}_2\text{OCl}_2$  (or  $\text{PbCl}_2 \cdot \text{PbO}$ ) is lead oxy-chlorid and  $\text{Pb}_2\text{Cl}_2\text{CO}_3$  (or  $\text{PbCl}_2 \cdot \text{PbCO}_3$ ) is lead chloro-carbonate.

Acid and basic salts when heated in the closed tube at a relatively high temperature (usually above  $200^\circ \text{C}$ .) give off water and this water is called **water of constitution**.

In other compounds water is more loosely held, and is given off on heating at a temperature varying from about  $100^\circ \text{C}$ . to  $200^\circ \text{C}$ . This is the so-called **water of crystallization**, but as Alexander Smith has pointed out this term is a misnomer, water not being necessary for crystallization. Many anhydrous compounds and minerals occur in well formed crystals. Salts which give off water at low temperatures are called **hydrates** or **hydrous salts**. The formula is written as if they contain water as such. Examples, hydrous calcium sulfate,  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ; hydrous sodium borate,  $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ . There may be various hydrates, for example,  $\text{MgSO}_4 \cdot \text{H}_2\text{O}$ ,  $\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$ , and  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ .

The following are examples of complicated salts which occur as minerals.  $\text{HNa}_3(\text{CO}_3)_2 \cdot 2\text{H}_2\text{O}$ , hydrous acid sodium carbonate;  $\text{Fe}_4(\text{OH})_2(\text{SO}_4)_5 \cdot 17\text{H}_2\text{O}$ , hydrous basic ferric sulfate.

### 3. DERIVATION OF CHEMICAL FORMULÆ

A mineral has a definite chemical composition and hence may be represented by a formula. The formula is obtained by dividing the percentage composition of the various elements or

radicals by the corresponding combining weights as found in a table of atomic weights (pages 164-5). The ratio of these expressed in the simplest whole numbers possible gives the empirical formula. Example: An analysis of chalcopyrite from Phoenixville, Pennsylvania, gave Smith the following:

	I	II	III	IV
Cu	32.85	÷ 63.6	= 0.516	34.57
Fe	29.93	÷ 55.8	= 0.536	30.54
S	36.10	÷ 32.1	= 1.121	34.89
Pb	0.35			

Dividing by the combining weights given in the second column we have the figures of the third column, lead being omitted. These numbers are nearly in the ratio 1:1:2, hence the formula  $\text{CuFeS}_2$ . The theoretical percentages for chalcopyrite are given in the fourth column.

Discrepancies in analyses may be explained in two ways. (1) Impurities may be present and should be eliminated before analysis if possible. If not, the analysis may be recalculated. (2) Similar metals or acid radicals may replace each other in various proportions. In this case the molecular ratios of replacing metals or acid radicals are added together. An analysis of brown sphalerite from Roxbury, Connecticut, gave Caldwell the percentage composition of column I. Dividing by the

	I	II	III	IV
Zn	63.36	÷ 65.5	= 0.967	} 1.031
Fe	3.60	÷ 55.8	= 0.064	
S	33.36	÷ 32.1	= 1.039	1.039

combining weights of column II we have the molecular ratios of III. The sum of the molecular ratios for Zn and Fe (1.031) is to the molecular ratio for S (1.039) practically as 1:1. Hence the formula,  $(\text{Zn,Fe})\text{S}$ , which means that iron replaces zinc in varying amounts. Analyses of sphalerite show an iron content varying from *nil* up to 18 per cent.

Analyses of oxids, haloids, sulfids, and sulfo-salts are given as

percentages of the elements. This cannot be done with the oxygen salts as there is no way of determining oxygen directly. So that the percentage composition of the oxygen salts must be expressed either as oxids or as metals and acid radicals. At present it is customary to use the oxids. This is in accordance with the electro-chemical theory of Berzelius in which dualistic formulæ were used. Thus  $\text{FeSO}_4$  was considered as  $\text{FeO} \cdot \text{SO}_3$ ,  $\text{FeO}$  being the base or electropositive radical and  $\text{SO}_3$ , the acid or electronegative radical. As these views are considered antiquated by modern chemists, it is preferable to employ the metals and acid radicals in stating the results of analysis. Thus  $\text{FeSO}_4$  may be given as  $\text{Fe}''$  and  $\text{SO}_4$ , indicating the valence of iron. The present author has given the results of analyses of oxygen salts (except the silicates) in this form, though he has had to recalculate the analyses. This method is especially applicable if haloids or sulfids are present. In the ordinary method there is an excess of oxygen equivalent to the amount of halogen or sulfur present which must be deducted. For example, apatite is  $\text{Ca}_5\text{F}(\text{PO}_4)_3$ . The calculated percentage compositions are:  $\text{CaO} = 55.5$ ;  $\text{P}_2\text{O}_5 = 42.3$ ;  $\text{F} = 3.8$ ; Total = 101.6. The excess over 100 per cent. is due to the fact that only part of the calcium is combined with the oxygen as can be seen by expressing the formula in another way.  $9\text{CaO} \cdot 3\text{P}_2\text{O}_5 \cdot \text{CaF}_2$ . The oxygen equivalent of  $\text{F}$  is  $\frac{1}{2}\text{O}$  with atomic weight of 8. The percentage compositions given above have been figured on the basis of formula weight of 512.5 ( $504.5 + 8$ ).  $512.5 : 504.5 :: 101.6 : 100$ . A much better way is to express the percentage composition thus:  $\text{Ca} = 39.7$ ;  $\text{F} = 3.8$ ;  $\text{PO}_4 = 56.5$ ; total = 100.0.

But in many silicates it is not possible to determine the silicic acid of which they are salts and in these cases nothing can be done except to use the oxids, antiquated though the method may be. In this book analyses of silicates are all given in the form of oxids. In the case of hydrous, acid, or basic salts of any kind, the water percentage is given as the determination of water is often a practical means of identifying a mineral.

Some facts regarding the relation between chemical composition and crystal form are important in the study of minerals, for upon these facts the commonly accepted classification of minerals largely rests.

#### 4. POLYMORPHISM

Many mineral substances exist in two or more distinct forms, that is, in crystals belonging to different crystal systems (not simply different crystal habits) and having dissimilar physical properties. Such compounds are called **polymorphs**. A familiar example is carbon which occurs as graphite in soft, opaque hexagonal crystals, and as diamond in very hard, transparent isometric crystals. Polymorphous elements like carbon are called **allotropic**. Among polymorphous minerals may be mentioned the following:

$\text{FeS}_2$	{	Pyrite—Isometric
		Marcasite—Orthorhombic
$\text{CaCO}_3$	{	Calcite—Hexagonal
		Aragonite—Orthorhombic
$\text{KAlSi}_3\text{O}_8$	{	Orthoclase—Monoclinic
		Microcline—Triclinic

The above minerals are **dimorphous**. The following minerals are **trimorphous**:

$\text{TiO}_2$	{	Rutile	—Tetragonal	$c=0.64$
		Octahedrite	—Tetragonal	$c=1.77$
		Brookite	—Orthorhombic	
$\text{Al}_2\text{SiO}_5$	{	Cyanite	—Triclinic	
		Andalusite	—Orthorhombic	$a=0.986, c=0.702$
		Sillimanite	—Orthorhombic	$a=0.970, c=?$

The three last mentioned minerals have the same empirical formula, but Groth has suggested that cyanite is  $(\text{AlO})_2\text{SiO}_3$ , and the other two,  $\text{Al}(\text{AlO})\text{SiO}_4$ .

Numerous examples of polymorphism occur in prepared com-

pounds. Sulfur may be prepared in at least four modifications:  $\alpha$ -sulfur is orthorhombic;  $\beta$ -sulfur, monoclinic;  $\gamma$ -sulfur, also monoclinic, but with different axial ratio from  $\beta$ -sulfur;  $\delta$ -sulfur, rhombohedral.

Mercuric iodid,  $\text{HgI}_2$ , exists in a red tetragonal modification (from solutions) and also in a yellow orthorhombic modification (from fusion or sublimation).

In many cases it is the temperature which determines the modification formed. Thus calcite forms from aqueous solutions below  $30^\circ \text{C}$ ., while aragonite forms above  $30^\circ \text{C}$ . For example, the crust formed in a tea-kettle is aragonite. Quartz ( $\text{SiO}_2$ ) forms below  $800^\circ \text{C}$ ., while tridymite (a modification of  $\text{SiO}_2$ ) forms above  $800^\circ \text{C}$ .

## 5. ISOMORPHISM

Many compounds of similar chemical composition, especially salts with the same acid radicals and related metals, have almost identical crystal forms. Such compounds are said to be **isomorphous**. Isomorphous substances have similar form, but except in the isometric system it does not mean that the form is identical. For example, the angle  $(110:1\bar{1}0)$  for barite,  $\text{BaSO}_4$ , is  $78^\circ 22\frac{1}{2}'$ , while for celestite,  $\text{SrSO}_4$ , it is  $75^\circ 50'$  and for anglesite,  $\text{PbSO}_4$ , it is  $76^\circ 16\frac{1}{2}'$ . Barite, celestite, and anglesite form an isomorphous group. Among prominent isomorphous groups of minerals are the following:

{ Pyrite	$\text{FeS}_2$
{ Smaltite	$(\text{Co}, \text{Ni})\text{As}_2$
{ Cobaltite	$\text{CoAsS}$
{ Gersdorffite	$\text{NiAsS}$
{ Marcasite	$\text{FeS}_2$
{ Arsenopyrite	$\text{FeAsS}$
{ Löllingite	$\text{FeAs}_2$
{ Glaucodote	$(\text{Co}, \text{Fe})\text{AsS}$
{ Safflorite	$\text{CoAs}_2$
{ Rammelsbergite	$\text{NiAs}_2$
{ Tetrahedrite	$\text{Cu}_3\text{SbS}_4$
{ Tennantite	$\text{Cu}_3\text{AsS}_4$



Ruby Silvers	{	Proustite	$\text{Ag}_3\text{AsS}_3$
	{	Pyrargyrite	$\text{Ag}_3\text{SbS}_3$
	{	Corundum	$\text{Al}_2\text{O}_3$
	{	Hematite	$\text{Fe}_2\text{O}_3$
	{	Cassiterite	$\text{SnO}_2$
	{	Rutile	$\text{TiO}_2$
	{	Diaspore	$\text{Al}(\text{OH})_3 \cdot \text{Al}_2\text{O}_3$
	{	Goethite	$\text{Fe}(\text{OH})_3 \cdot \text{Fe}_2\text{O}_3$
	{	Manganite	$\text{Mn}(\text{OH})_3 \cdot \text{Mn}_2\text{O}_3$
	{	Calcite	$\text{CaCO}_3$
	{	Magnesite	$\text{MgCO}_3$
	{	Ankerite	$\text{Ca}(\text{Mg}, \text{Fe})\text{CO}_3$
	{	Siderite	$\text{FeCO}_3$
	{	Rhochrosite	$\text{MnCO}_3$
	{	Smithsonite	$\text{ZnCO}_3$
	{	Aragonite	$\text{CaCO}_3$
	{	Strontianite	$\text{SrCO}_3$
	{	Witherite	$\text{BaCO}_3$
	{	Cerussite	$\text{PbCO}_3$
	{	Fluor-apatite	$\text{Ca}_5\text{F}(\text{PO}_4)_3$
	{	Chlor-apatite	$\text{Ca}_5\text{Cl}(\text{PO}_4)_3$
	{	Dahllite	$\text{Ca}_5(\text{CO}_3)_2(\text{PO}_4)_3$
	{	Voelckerite	$\text{Ca}_5\text{O}_3(\text{PO}_4)_3$
	{	Svabite	$\text{Ca}_5\text{F}(\text{AsO}_4)_3$
	{	Pyromorphite	$\text{Pb}_5\text{Cl}(\text{PO}_4)_3$
	{	Mimetite	$\text{Pb}_5\text{Cl}(\text{AsO}_4)_3$
	{	Vanadinite	$\text{Pb}_5\text{Cl}(\text{VO}_4)_3$
	{	Barite	$\text{BaSO}_4$
	{	Celestite	$\text{SrSO}_4$
	{	Anglesite	$\text{PbSO}_4$
	{	Ilmenite	$\text{FeTiO}_3$
	{	Geikielite	$\text{MgTiO}_3$
	{	Pyrophanite	$\text{MnTiO}_3$
	{	Senaite	$(\text{Fe}, \text{Mn}, \text{Pb})\text{TiO}_3$
Garnets	{	Grossularite	$\text{Ca}_3\text{Al}_2(\text{SiO}_4)_3$
	{	Pyrope	$\text{Mg}_3\text{Al}_2(\text{SiO}_4)_3$
	{	Almandite	$\text{Fe}_3\text{Al}_2(\text{SiO}_4)_3$
	{	Spessartite	$\text{Mn}_3\text{Al}_2(\text{SiO}_4)_3$
	{	Andradite	$\text{Ca}_3\text{Fe}_2(\text{SiO}_4)_3$
	{	Uvarovite	$\text{Ca}_3\text{Cr}_2(\text{SiO}_4)_3$

Many isomorphous compounds are capable of crystallizing out together in various proportions forming what are known as **isomorphous mixtures**. There are many such cases among minerals and this fact is very useful in interpreting mineral analyses. Ankerite is an isomorphous mixture of  $\text{CaCO}_3$  with  $\text{MgCO}_3$  and  $\text{FeCO}_3$  and is represented by the formula  $\text{Ca}(\text{MgFe})\text{CO}_3$ , which means that the proportions of Ca, Mg, and Fe vary in different specimens and that the molecular ratios of Mg and Fe together equal that of Ca. Among prominent isomorphous mixtures are: Sphalerite  $(\text{Zn},\text{Fe})\text{S}$ , smaltite  $(\text{Co},\text{Ni})\text{As}_2$ , tetrahedrite  $(\text{Cu},\text{Fe},\text{Zn},\text{Hg},\text{Ag})_8(\text{Sb},\text{As})\text{S}_8$ , columbite  $(\text{Fe},\text{Mn})(\text{Nb},\text{Ta})_2\text{O}_6$ , campylite  $\text{Pb}_5\text{Cl}(\text{As},\text{P})_3\text{O}_{12}$ , endlichite  $\text{Pb}_5\text{Cl}(\text{As},\text{V})_3\text{O}_{12}$ , pisanite  $(\text{Fe},\text{Cu})\text{SO}_4 \cdot 7\text{H}_2\text{O}$ , wolframite  $(\text{Fe},\text{Mn})\text{WO}_4$ , actinolite  $\text{Ca}(\text{Mg},\text{Fe})_3(\text{SiO}_3)_4$ , epidote  $\text{Ca}_2(\text{Al},\text{Fe})_3(\text{OH})(\text{SiO}_3)_3$ . The garnets are isomorphous mixtures of minerals given on page 174. It is rare to find an analysis of garnet that will correspond exactly to any one of these formulae.

The physical properties of isomorphous mixtures vary continuously and for this reason the term **solid solution** is sometimes used. Some authors restrict the term isomorphous to compounds which are capable of forming mixed crystals. But this hardly seems feasible with minerals, for most of them are intractable compounds.

## 7. BLOWPIPE ANALYSIS

The advantage of blowpipe analysis lies in the fact that the tests are simple, the apparatus portable, and the reagents few in number. By means of the blowpipe an intense heat (about  $1500^\circ \text{C.}$ ) can be obtained on a small scale, and a variety of chemical effects can be brought about. At the same time it is the author's opinion that with a few exceptions, blowpipe analysis is of value only in the determination of minerals.

Blowpipe analysis will be discussed under four headings: (8) apparatus, (9) reagents, (10) operations, and (11) select tests. Section 10 may be used in preliminary tests and also as determi-

native tables, while tests for the metals and acid radicals may be found in section 11, arranged alphabetically by elements.

### 8. APPARATUS USED IN BLOWPIPE ANALYSIS

**Blowpipe.** The blowpipe is made in a variety of forms. The simplest blowpipe is a brass tube about 10 inches long bent at one end. A bulb is sometimes added to condense moisture. A more elaborate form is a nickel-plated tube with a moisture chamber at one end and a smaller tube at right angles which is provided with either a brass or a platinum tip. Where gas is available, the gas blowpipe is undoubtedly the most convenient form on account of the perfect control of the flame. The gas blowpipe (Fig. 386, page 181) is similar to the nickel-plated form just described, but the smaller right-angled tube is a double one, the inner one for air, the outer one for gas.

**Fuel.** Gas is the most convenient and commonly used fuel. If a Bunsen burner is used, it is well to use a small tube which fits the top of the Bunsen burner, and is provided with a flange in which the tip of the blowpipe rests. The luminous flame of the Bunsen burner should be used with the blowpipe.

Where gas is not available, alcohol, lard oil, or olive oil may be burned in a lamp with a wick. Candles are even more convenient. For field use a good combination is alcohol for heating and candles for use with the blowpipe.

**Charcoal.** Slabs of charcoal about 4 inches long, 1 inch wide, and  $\frac{1}{4}$  inch thick are used. They may be purchased from dealers in chemical apparatus.

**Plaster.** A paste of plaster of Paris with water is poured out on oiled glass in sheets about  $\frac{1}{4}$  inch thick. Before hardening, it is marked off in rectangles about 4 inches long and 1 inch wide.

**Platinum Tipped Forceps.** These forceps are essential for testing the fusibility of minerals, and are useful for other purposes. Arsenic, antimony, lead, and copper minerals should be fused on charcoal, for these metals alloy with platinum.

**Hammer.** A small square-faced hammer of about one-fourth pound weight is indispensable.

**Anvil.** A small block of steel, square or rectangular in cross-section, and about  $\frac{1}{2}$  inch thick is convenient for powdering minerals.

**Platinum Wire.** No. 27 platinum wire is the best size for general use. The wire may be fused into a piece of glass tubing, or held in a special holder made for the purpose.

**Test Tubes.** The most convenient size is 4 inches long and  $\frac{1}{2}$  inch in diameter.

**Glass Tubing.** Soft glass tubing of 7 mm. outside diameter is best for most purposes, but it is well to have a variety of sizes. For some tests hard glass tubing is preferable.

**Watch Glasses.** These are needed especially for solubility tests. The best size is 2 inches in diameter.

**Magnet.** A magnetized knife-blade answers the same purpose and is more convenient.

**Lens.** A Coddington or aplanatic triplet of  $\frac{3}{4}$  inch focus is recommended. A **triangular file**, **blue glass**, **funnels**, and **filter-paper** are also essential.

The following pieces of apparatus are not essential, but will be found very useful.

**Diamond Mortar.** A mortar made of a piece of cylindrical tool-steel about 1 inch long and about 1 inch in diameter, with a convenient size cylindrical cavity and pestle to fit, is very convenient for reducing a mineral to a coarse powder.

**Agate Mortar.** A small agate mortar,  $1\frac{1}{2}$  inches in diameter, is used for fine grinding of minerals.

**Steel Pliers** are used for breaking off fragments of minerals.

**Platinum Foil.** A thin sheet of platinum about  $\frac{1}{2}$  by  $\frac{3}{4}$  inch may be used for soda fusions.

**Dropping Bulbs** are useful for reagents that are needed in small amounts, such as  $\text{Co}(\text{NO}_3)_2$ .

Small beakers, crucibles, wash-bottles, etc., may often be used to advantage.

## § 9. REAGENTS USED IN BLOWPIPE ANALYSIS

*A. Dry Reagents*

Dry reagents should be kept in wide mouthed glass bottles. It is convenient to have a set of four or six of these bottles in a wooden stand.

**Soda or Sodium Carbonate**,  $\text{Na}_2\text{CO}_3$ . Baking soda ( $\text{NaHCO}_3$ ) may be used instead. Soda is used principally for fusions.

**Borax**,  $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$  is used principally for bead tests. The ordinary commercial salt can be used. Borax glass is simply fused borax, used in silver cupellation.

**Sodium Metaphosphate**,  $\text{NaPO}_3$ . This is used for the bead tests, in which salt of phosphorus,  $\text{HNaNH}_4\text{PO}_4 \cdot 4\text{H}_2\text{O}$ , is usually employed. It can be made by fusing salt of phosphorus, and is much more convenient, as a salt of phosphorus bead usually drops off the loop of platinum wire when heated.

**Potassium Acid Sulfate**,  $\text{KHSO}_4$ . This is used in bismuth flux, in boracic acid flux, and also independently.

**Bismuth Flux** is made by grinding together 1 part KI, 1 part  $\text{KHSO}_4$ , and 2 parts S. It is used on plaster tablets and also on charcoal.

**Boracic Acid Flux** is a mixture of 1 part of finely powdered fluorite ( $\text{CaF}_2$ ) with 3 parts of  $\text{KHSO}_4$ .

**Cupric Oxid**,  $\text{CuO}$ . Powdered malachite may be used instead.

**Tin**. Ordinary tin-foil (sheet lead with a thin coating of tin) is used as a reducing agent.

**Test Lead**. Lead in a granulated form such as is used in assaying.

**Bone-Ash**, such as is used in assaying, is moulded into cupels on charcoal.

*B. Wet Reagents*

The following are the more important wet reagents used in the determination of minerals, though occasionally any of the reagents of the chemical laboratory may be found useful.

**Hydrochloric Acid**,  $\text{HCl}$ . Two parts concentrated acid (sp. gr.

1.20) with 3 parts distilled water is the acid used for general purposes. (5N.)\*

**Nitric Acid**,  $\text{HNO}_3$ . One part concentrated acid (sp. gr. 1.42) with 2 parts water. (5N.)

**Sulfuric Acid**,  $\text{H}_2\text{SO}_4$ . One part concentrated acid (sp. gr. 1.84) with 4 parts of water (5N). It should be diluted with great care by pouring acid into the water rather than the reverse.

**Citric Acid**. As this is a solid it may be used in the field for testing carbonates. It is only necessary to make a water solution.

**Aqua Regia** is a mixture of 3 parts of conc.  $\text{HCl}$  and 1 part of conc.  $\text{HNO}_3$ . It is made up when needed.

**Ammonium Hydroxid**,  $\text{NH}_4\text{OH}$ . One part of concentrated  $\text{NH}_4\text{OH}$  (sp. gr. 0.96) to 4 parts of solution.

**Ammonium Oxalate**,  $(\text{NH}_4)_2\text{C}_2\text{O}_4 \cdot 2\text{H}_2\text{O}$ . 40 grams of salt to a liter of solution. ( $\frac{1}{2}\text{N}$ .)

**Sodium Acid Phosphate**,  $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$ . 60 grams to a liter of solution. ( $\frac{1}{2}\text{N}$ .)

**Ammonium Molybdate**,  $(\text{NH}_4)_2\text{MoO}_4$ . It is difficult to prepare this reagent. Dissolve 100 grams of  $\text{MoO}_3$  in 250 ccm.  $\text{NH}_4\text{OH}$  (sp. gr. 0.96) with 250 ccm. of water. After cooling, pour this solution into 750 ccm.  $\text{HNO}_3$  (sp. gr. 1.2) with 750 ccm. water while stirring.

**Silver Nitrate**,  $\text{AgNO}_3$ . 43 grams of the salt to a liter of solution. ( $\frac{1}{2}\text{N}$ .)

**Barium Chlorid**,  $\text{BaCl}_2 \cdot 2\text{H}_2\text{O}$ . 61 grams of salt to a liter of solution. ( $\frac{1}{2}\text{N}$ .)

**Cobalt Nitrate**,  $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ . 73 grams of the salt to a liter of solution. ( $\frac{1}{2}\text{N}$ .)

### *C. Additional Reagents used in Qualitative Analysis*

**Acetic Acid**,  $\text{HC}_2\text{H}_3\text{O}_2$ . 30 per cent. acid. (5N.)

**Alcohol**. 95 per cent. ethyl alcohol.\*

\*N means a normal solution, i. e., one that contains one gram-equivalent of the substance in one liter, a gram atom of hydrogen being the unit.

**Ammonium Carbonate**,  $(\text{NH}_4)_2\text{CO}_3$ . 192 grams to a liter of solution, including 100 ccm. of  $\text{NH}_4\text{OH}$ . (4N).

**Ammonium Chlorid**,  $\text{NH}_4\text{Cl}$ . 267 grams to a liter of solution. (5N). The solid reagent is also used for some purposes.

**Ammonium Sulfid**,  $(\text{NH}_4)_2\text{S}$ . Saturate conc.  $\text{NH}_4\text{OH}$  with  $\text{H}_2\text{S}$ , and add an equal volume of  $\text{NH}_4\text{OH}$ . Dilute with three volumes of water. (4N.)

**Ammonium Sulfid, Yellow**,  $(\text{NH}_4)_2\text{S}_x$ . Made by adding flowers of sulfur to  $(\text{NH}_4)_2\text{S}$ .

**Barium Hydroxid**,  $\text{Ba}(\text{OH})_2 \cdot 8\text{H}_2\text{O}$ .

**Calcium Carbonate**,  $\text{CaCO}_3$ . The solid reagent.

**Chloroplatinic Acid**,  $\text{H}_2\text{PtCl}_6$ . This is made by dissolving scrap platinum (after cleaning) in aqua regia.

**Ether-Alcohol**. Equal volumes of ether and absolute alcohol.

**Ferrous Sulfate**,  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ . Concentrated solution.

**Lead Acetate**,  $\text{Pb}(\text{C}_2\text{H}_3\text{O}_2)_2 \cdot 3\text{H}_2\text{O}$ . 95 grams to a liter of solution. ( $\frac{1}{2}\text{N}$ .)

**Potassium Chromate**,  $\text{K}_2\text{CrO}_4$ . 49 grams to a liter of solution. ( $\frac{1}{2}\text{N}$ .)

**Potassium Cyanid**,  $\text{KCN}$ . 33 grams to a liter of solution. ( $\frac{1}{2}\text{N}$ .)

**Potassium Ferricyanid**,  $\text{K}_3\text{Fe}(\text{CN})_6$ . 55 grams to a liter of solution. ( $\frac{1}{2}\text{N}$ .)

**Potassium Ferrocyanid**,  $\text{K}_4\text{Fe}(\text{CN})_6 \cdot 3\text{H}_2\text{O}$ . 53 grams to a liter of solution. ( $\frac{1}{2}\text{N}$ .)

**Potassium Hydroxid**,  $\text{KOH}$ . Solid reagent.

**Sodium Acetate**,  $\text{NaC}_2\text{H}_3\text{O}_2$ . The solid dissolved in ten parts of water.

**Sodium Carbonate**,  $\text{Na}_2\text{CO}_3$ . Solid reagent.

**Sodium Cobaltic Nitrite**,  $\text{Na}_3\text{Co}(\text{NO}_2)_6$ . This is made by adding 1 part of  $\text{Co}(\text{NO}_3)_2$  solution to 3 parts of acetic acid and 5 parts of a 10 per cent. solution of  $\text{NaNO}_2$ .

**Sodium Hydroxid**,  $\text{NaOH}$ . Solid reagent.

**Sodium Nitrate**,  $\text{NaNO}_3$ . Solid reagent.

**Stannous Chlorid**,  $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$ . 56 grams to a liter of solution. ( $\frac{1}{2}\text{N}$ .)

**Tartaric Acid**,  $\text{C}_4\text{H}_4\text{O}_6$ .

## 10. THE OPERATIONS OF BLOWPIPE ANALYSIS

The list of tests given here serves both as an outline to follow with known substances, and also as determinative tables for unknown minerals. Only important tests are included so that to be of value decided results must be obtained.

### I. Use of the Blowpipe.

To produce a steady flame, maintain a reservoir of air by keeping the checks slightly distended, and by breathing through the nose.

**Oxidizing Flame (O.F.).** The extreme outer tip (Fig. 386) of a *small* flame produced by a rather *strong* blast of air is most favorable for oxidation. If a candle, lamp, or Bunsen burner is

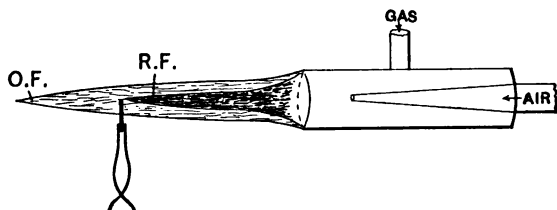


FIG. 386.

used, the tip of the blowpipe is held just *within* the flame. One's ability to produce a good oxidizing flame may be judged by fusing borax on a  $\frac{1}{8}$  inch loop of platinum wire and then adding a little  $\text{MoO}_3$ . The bead should be colorless.

**Reducing Flame (R.F.).** The tip of the inner luminous cone (Fig. 386) of a *large* flame produced by a *gentle* blast of air is most favorable for reduction. If a candle, lamp, or Bunsen burner is used, the blowpipe tip is held just *outside* the flame and the whole flame is directed toward the assay. A borax bead made amethyst colored with a little  $\text{MnO}_2$  in O.F. should become colorless when heated in a good reducing flame. The reducing flame should be luminous, and just hot enough to prevent the deposition of soot.



**II. Flame Tests.**

In the high temperature of the blowpipe flame many compounds are volatilized. The colors produced are often characteristic, and should be viewed against a black background such as a piece of charcoal. The chlorids are, as a rule, the most volatile compounds of the metals, so HCl should be used, but in some cases  $H_2SO_4$  is better. Platinum wire is used except for compounds of As, Sb, Pb, and Cu, which may be heated on charcoal. The wire should be cleaned with HCl after each test, but it should never be placed in a reagent bottle on account of danger of contaminating the reagent.

**Red Flames.**

Purplish red—**lithium** compounds.

Crimson—**strontium** compounds.

Orange red—**calcium** compounds.

**Yellow Flames.**

Intense yellow (masked by blue glass)—**sodium** compounds.

**Green Flames.**

Yellowish green—**barium** compounds.

Yellowish green—**molybdenum** compounds.

Emerald green—**copper** compounds (without HCl).

Bright green (use  $H_2SO_4$ )—**boron** compounds.

Pale bluish green (use  $H_2SO_4$ )—**phosphates**.

Pale bluish green—**tellurium** compounds.

Pale bluish green—**antimony** compounds.

Bluish green—**zinc** compounds.

**Blue Flames.**

Azure blue—**copper** compounds (with HCl).

Pale blue—**arsenic** compounds.

Pale blue—**lead** compounds.

**Violet Flames.**

Pale reddish violet (use blue glass)—**potassium** compounds.

The spectroscope must be used to detect such elements as rubidium, calcium, thallium, indium, etc., and also to detect very small amounts of the above mentioned elements.

### III. Open Tube Tests.

Glass tubes about 4 inches long and open at *both* ends are used. The substance is placed about 1 inch from one end of tube. The tube is heated gently in a horizontal position at first and then is gradually inclined while still heating, thus producing a current of air.

Odor of burning matches ( $\text{SO}_2$ )—**sulfids** and **sulfo-salts**.

Sublimate of minute brilliant crystals ( $\text{As}_2\text{O}_3$ )—**arsenids** and **sulfarsenites**.

Non-volatile amorphous sublimate ( $\text{Sb}_2\text{O}_4$ ) on under side of tube—**antimony sulfid** and **sulfantimonites**.

Gray metallic globules (Hg)—**mercury sulfid**.

### IV. Closed Tube Tests.

Glass tubes closed at *one* end are used. Two closed tubes may be made at the same time by fusing a piece of tubing about 5 inches long at its middle point and pulling it apart when hot. Tubes should be clean and dry before using.

#### 1. Change in Appearance.

Decrepitates (flies to pieces)—characteristic of many minerals.

Turns black—**copper** minerals.

Turns dark red—**iron** minerals.

Turns yellow—**lead** minerals.

Turns yellow (white on cooling)—**zinc** minerals.

#### 2. Formation of Sublimates.

Yellow sublimate (S)—some **sulfids**.

Black metallic mirror (As)—**arsenids**.

Reddish yellow ( $\text{AsS}$ )—**arsenic sulfids** and **sulfarsenites**.

Reddish brown ( $\text{Sb}_2\text{S}_2\text{O}$ )—**antimony sulfids** and **sulfantimonites**.

White volatile sublimate—**ammonium** salts.

Water ( $\text{H}_2\text{O}$ )—**hydroxids**, **hydrous**, **basic**, and **acid** salts.

#### 3. Formation of Gases.

Colorless and odorless ( $\text{CO}_2$ )—**carbonates** (detected by  $\text{Ba}(\text{OH})_2$ ).

Colorless and odorless (O)—**manganese dioxids** (detected by glowing charcoal).

Brownish-red and pungent odor ( $\text{NO}_2$ )—**nitrates**.

## V. Treatment on Charcoal.

The substance, either alone or intimately mixed with some reagent, is heated in a shallow circular cavity, at one end of the charcoal, made by revolving a coin or end of a knife handle. O.F. or R.F. is used according to the desired effect.

### 1. Evolution of Gas.

Odor of burning matches ( $\text{SO}_2$ )—**sulfids and sulfo-salts** (use O.F.).

Arsin odor ( $\text{AsH}_3$ )—**arsenids and sulfarsenites** (use R. F.).

### 2. Formation of Sublimates. (Use O. F.).

White sublimate near assay ( $\text{Sb}_2\text{O}_3$ )—**antimony compounds**.

White sublimate far from assay ( $\text{As}_2\text{O}_3$ )—**arsenic compounds**.

White sublimate, yellow when hot ( $\text{ZnO}$ )—**zinc compounds**.

White sublimate, yellow near assay ( $\text{PbSO}_4$ )—**lead sulfid**.

Yellow sublimate ( $\text{PbO}$ )—**lead compounds**.

Yellow sublimate  $\text{Bi}_2\text{O}_3$ —**bismuth compounds**.

### 3. Reduction with Soda.

Mix intimately 1 part of the finely powdered substance with 3 parts of soda ( $\text{Na}_2\text{CO}_3$ ) and fuse in R. F. on charcoal.

Magnetic particles ( $\text{Fe}_3\text{O}_4, \text{Ni, Co}$ )—**iron, nickel, and cobalt compounds**.

Metallic button, gray and malleable (Pb)—**lead compounds**.

Metallic button, malleable but brittle on edges (Bi)—**bismuth compounds**.

Metallic button, malleable white (Ag)—**silver compounds**.

Metallic button, malleable yellow (Au)—**gold compounds**.

Metallic button, malleable red (Cu)—**copper compounds**.

Metallic button, malleable white (Sn)—**tin compounds**.

### 4. Soda Fusion Test for Sulfur.

An intimate mixture of a finely powdered sulfid or sulfo-salt, with about three parts of soda is heated in O.F. on a thin sheet of

mica (or platinum, if absence of As, Sb, Pb, and Cu is assured). The fused mass placed on a bright silver coin with several drops of water and crushed will give a black stain ( $\text{Ag}_2\text{S}$ ). The reactions are:  $\text{R}''\text{S} + \text{Na}_2\text{CO}_3 = \text{Na}_2\text{S} + \text{R}''\text{CO}_3$ .  $\text{Na}_2\text{S} + 2\text{Ag} + \text{H}_2\text{O} + \text{O} = \text{Ag}_2\text{S} + 2\text{NaOH}$ . Tellurids give the same test.

Try a blank test to see if gas or soda contains sulfur.

Sulfates also give this test if heated in a strong R.F. on charcoal instead of on mica. Powdered charcoal helps the reaction. The sulfur compounds sink into the charcoal, hence the same spot cannot be used more than once.

#### 5. Treatment with Cobalt Nitrate.

The substance is heated intensely on charcoal before and after adding a dilute solution of cobalt nitrate. In this way cobalt aluminate, cobalt zincate, etc., are formed.

Deep blue coloration—infusible **aluminum** compounds and **zinc silicates**. (Almost any *fusible* substance will give a blue color for a cobalt glass is formed.)

Bright green coloration—**zinc** compounds, except the silicates which give a blue coloration.

Bluish-green coloration—**tin** compounds.

✓ Pale pink coloration—**magnesium** compounds (not very satisfactory).

#### VI. Treatment on Plaster with Bismuth Flux.

An intimate mixture of the substance with an equal quantity of bismuth flux (2 parts S, 1 part KI, and 1 part  $\text{KHSO}_4$ ) is heated gently at one end of a plaster tablet. In this way iodids of the metals are obtained.

Yellow sublimate ( $\text{PbI}_2$ )—**lead** compounds.

Orange sublimate stippled with peach-red ( $\text{SbI}_3$ )—**antimony** compounds.

Purplish-chocolate sublimate ( $\text{BiI}_3$ )—**bismuth** compounds.

Scarlet sublimate (dark greenish-yellow if overheated)

• ( $\text{HgI}_2$ )—**mercury** compounds.

Deep blue sublimate ( $\text{MoI}_6$ ?)—**molybdenum** compounds.

**VII. Treatment on Charcoal with Bismuth Flux.**

As above but with charcoal instead of plaster as a support.

Greenish-yellow sublimate ( $\text{PbI}_2$ )—**lead** compounds.

Scarlet sublimate ( $\text{BiI}_3$ )—**bismuth** compounds.

Faint yellow sublimates ( $\text{HgI}_2$ , etc.)—**mercury, arsenic, and antimony** compounds.

**VIII. Borax Bead Tests.**

Borax beads are made by fusing borax in an  $\frac{1}{8}$ -inch loop of platinum wire. Great care should be used in O.F. and R.F. Sulfids should be first roasted by gently heating the powdered substance spread out on charcoal. It is well to preserve the beads in a little frame or glass tube for future reference. Many elements giving colorless or pale yellow beads are not mentioned. The colors refer to cold beads, except when otherwise mentioned.

	Violet	Blue	Green	Red	Brown	Yellow	Colorless
Co		O.F., R.F.					
Cr			O.F., R.F.				
Cu		O.F.		R. F. (opaque)			
Fe			R.F.			O.F.	
Mn	O.F.						R.F.
Mo					R.F.		O.F.
Ni	O.F. (hot)				O.F. (cold)		R.F. (turbid gray)
Ti	R.F.						O.F.
U			R.F.			O.F.	
V			R.F.				O.F.
W						R.F.	O.F.

**IX. Sodium Metaphosphate Bead Tests.**

Beads of sodium metaphosphate,  $\text{NaPO}_3$ , are made just as with borax. Salt of phosphorus or microcosmic salt,  $\text{HNaNH}_4\text{-PO}_4\cdot 4\text{H}_2\text{O}$  may also be used, for on heating it loses  $\text{NH}_3$  and  $\text{H}_2\text{O}$ , and is converted into  $\text{NaPO}_3$ . The colors refer to cold beads.

	Violet	Blue	Green	Red	Yellow	Colorless
Co		O.F., R.F.				
Cr			O.F., R.F.			
Cu		O.F.		R.F. (opaque)		
Fe					O.F. (pale)	O.F., R.F.
Mn	O.F.					R.F.
Mo			R.F.			O.F.
Ni					O.F., R.F.	
Ti	R.F.					O.F.
U			O.F., R.F.			
V			R.F.		O.F.	
W		R.F.				O.F.

Silica is insoluble in a  $\text{NaPO}_3$  bead, while with silicates, the bases dissolve (sometimes coloring the bead) while the silica remains as a translucent mass, often the shape of the original fragment, which floats around in the bead. A few other compounds, such as  $\text{Al}_2\text{O}_3$ , are also insoluble in a  $\text{NaPO}_3$  bead or are very slowly soluble.

**X. Reduction Color Tests.**

Saturate several  $\text{NaPO}_3$  beads with the substance, and heat on charcoal with metallic tin in R.F. Dissolve in dilute  $\text{HCl}$ , add tin, and then boil.

Violet solution—**titanium** compounds.

Deep blue solution—**tungsten** compounds.

Brown solution—**molybdenum** compounds.

Green solution—**chromium**, **uranium**, and **vanadium** compounds.

**XI. Soda Bead Tests.**

Beads of soda are made as with borax and sodium metaphosphate. Use O.F.

Bluish-green opaque bead ( $\text{Na}_2\text{MnO}_4$ )—**manganese** compounds (a very delicate test).

Yellow opaque bead ( $\text{Na}_2\text{CrO}_4$ )—**chromium** compounds.

Effervescence—**silica**.  $\text{Na}_2\text{CO}_3 + \text{SiO}_2 = \text{Na}_2\text{SiO}_3 + \text{CO}_2$ . (The bead will be clear if equal molecular quantities are used.)

**XII. Treatment with Acid Potassium Sulfate.**

The substance is mixed with  $\text{KHSO}_4$  and heated in a test-tube or closed tube.

Red-brown fumes with pungent odor ( $\text{NO}_2$ )—**nitrates**.

Colorless gas with  $\text{HCl}$  odor ( $\text{HCl}$ )—**chlorids**.

Colorless gas which etches glass ( $\text{HF}$ )—**fluorids**.

Colorless gas with disagreeable odor ( $\text{H}_2\text{S}$ )—**sulfids**.

Colorless, odorless gas ( $\text{CO}_2$ )—**carbonates**.

**XIII. Fusibility Tests.**

Long thin splinters of the mineral about 1 mm. in diameter held with platinum-tipped forceps or wrapped with a coil of platinum wire are heated in the hottest part of the flame which is

just beyond the tip of the inner cone (see Fig. 386, page 181) of a small sharp O.F. flame (rather strong blast). Metallic substances should be heated on charcoal as they may contain As, Sb, or Pb which will alloy with the platinum. Powders or substances which fly to pieces when heated may be ground into a paste with a little water, which after careful drying can be heated in the forceps or on charcoal.

### Scale of Fusibility

1. Fuses easily in luminous flames (gas or candle)—**stibnite**.
2. Fuses with difficulty in luminous flame—**chalcopyrite**.
3. Fuses easily in blowpipe flame—**almandite garnet**.
4. Fuses on edges easily in blowpipe flame—**actinolite**.
5. Fuses on edges with difficulty—**orthoclase**.
6. Fuses only on thinnest edges—**enstatite**.
7. Infusible, even on thinnest edges—**quartz**.

Not only the degree, but also the manner of fusion should be noted. The substance may fuse either to a clear, opaque, or colored glass, quietly, with intumescence (bubbling), or with exfoliation (spreading out like leaves of a book).

### XIV. Silver Cupellation.

A qualitative test for silver in ores may easily be carried out by means of the blowpipe. The method is similar to that used in assaying except that it is on a smaller scale.

By using an assay centner (100 mg.) of ore and measuring the silver button obtained on an ivory scale made for the purpose, one may obtain quantitative results which, after some practice, are very satisfactory.

(1) Mix finely powdered ore intimately with one volume of borax glass (made by fusing borax), and one volume of test lead. If ore is galena, it is not necessary to add test lead. (2) Fuse mixture in a deep cavity in charcoal with a strong R.F. for several



minutes. (3) When cool remove lead from charcoal and hammer off the slag. (4) Add fresh borax glass and heat in O.F. until the quantity of lead is considerably diminished. Again hammer off *every particle* of the slag. (5) Prepare a cupel by filling a large cavity in charcoal with *very slightly* moistened bone-ash and making a smooth concave depression with a mold (the end of a large test-tube will do). Heat cupel gently and remove all loose particles. (6) Place the cube of lead on the cupel and fuse in O.F. by blowing across the top of it, using a small flame and strong blast. The oxidation produces a thin film of lead oxid showing interference colors, but when the lead is all absorbed, the film suddenly disappears or "blicks," and a minute sphere of silver, which may also contain gold, remains. If the button "freezes" or is not spherical, it is better to begin again.

## XV. Solubility Tests.

In the absence of any special phenomena the only accurate way of testing solubility is to boil the solvent with the substance for some time and then to filter or decant the clear liquid and evaporate to dryness. A residue indicates that the substance is soluble. If in doubt as to the solubility run a blank test with an equal quantity of solvent alone. A water solution of the residue gives a precipitate with  $\text{Na}_2\text{CO}_3$ , except in the case of alkali compounds, but among minerals these are all readily soluble in water.

Soluble in water—nitrates, some chlorids, some sulfates, some borates, some carbonates.

Soluble in  $\text{HCl}$ —all carbonates, some sulfids, some sulfates, borates, some phosphates, some silicates (see p. 241-244), iron oxids, and iron hydroxids.

Soluble in  $\text{HNO}_3$ , but insoluble in  $\text{HCl}$ —most sulfids and sulfosalts.

Soluble in aqua regia—gold and platinum.

Soluble in  $\text{HF}$ —silica and nearly all the silicates.

Insoluble in acids but soluble in other liquids—**cerargyrite**, soluble in  $\text{NH}_4\text{OH}$ ; **anglesite**, soluble in  $\text{NH}_4\text{C}_2\text{H}_3\text{O}_2$ ; **sulfur**, soluble in  $\text{CS}_2$ .

Insoluble, but decomposed by fusion with  $\text{Na}_2\text{CO}_3$ —most **silicates**, **chromite**, **wolframite**, **barite**, and **celestite**. For method of treatment see note 4, for silicates, p. 203.

Insoluble, not completely decomposed by soda fusion, but decomposed by fusion with  $\text{KOH}$ —**cassiterite**, **corundum**, and **rutile**.

#### Evolution of Gas.

Colorless, odorless gas ( $\text{CO}_2$ )—**carbonates**.

Colorless gas with disagreeable odor ( $\text{H}_2\text{S}$ )—**some sulfids**.

Colorless, pungent gas ( $\text{Cl}$ )—**manganese dioxid**.

Brown red, pungent gas ( $\text{NO}_2$ )—**sulfids**.

#### Color of Solution.

Amber solution—**iron** compounds.

Green solution—**copper** and **nickel** compounds.

Blue solution—**copper** compounds.

Pale red solution—**cobalt** compounds.

#### Insoluble Residue.

Gelatinous residue—**some silicates**.

White residue ( $\text{PbSO}_4$ ), ( $\text{HSbO}_3$ ), ( $\text{AgCl}$ )—**lead**, **antimony**, and **silver** minerals.

Yellow residue ( $\text{WO}_3$ )—**calcium tungstate**.

### XVI. Wet Tests and Group Reagents.

#### A. Wet Tests for Bases

**HCl** precipitates **AgCl**, **HgCl**, and **PbCl<sub>2</sub>**.

**H<sub>2</sub>S** in acid solutions precipitates **Ag<sub>2</sub>S**, **PbS**, **HgS** + **Hg**, **Bi<sub>2</sub>S<sub>3</sub>**, **CuS**, **HgS**, **As<sub>2</sub>S<sub>3</sub>**, **As<sub>2</sub>S<sub>3</sub>** + **S**, **Sb<sub>2</sub>S<sub>3</sub>**, **SnS**, and **SnS<sub>2</sub>**.

**NH<sub>4</sub>OH** in the presence of HCl (or NH<sub>4</sub>Cl) precipitates Pb(OH)<sub>2</sub>, Hg<sub>2</sub>NH<sub>2</sub>Cl, HgNH<sub>2</sub>Cl, BiO(OH), SbO(OH), Sn(OH)<sub>2</sub>, Sn(OH)<sub>4</sub>, Al(OH)<sub>3</sub>, Cr(OH)<sub>3</sub>, Fe(OH)<sub>3</sub>, Fe(OH)<sub>2</sub>, and also Ca<sub>3</sub>(PO<sub>4</sub>)<sub>2</sub>, CaF<sub>2</sub>, and Ca(BO<sub>2</sub>)<sub>2</sub>.

**(NH<sub>4</sub>)<sub>2</sub>S** in neutral solutions precipitates Ag<sub>2</sub>S, PbS, HgS, CuS, Bi<sub>2</sub>S<sub>3</sub>, Sb<sub>2</sub>S<sub>3</sub>, SnS, Al(OH)<sub>3</sub>, Cr(OH)<sub>3</sub>, FeS, FeS + S, ZnS, MnS, CoS, and NiS.

**(NH<sub>4</sub>)<sub>2</sub>CO<sub>3</sub>** precipitates from alkaline solutions carbonates of all the non-alkali metals except Mg. With Ag, Cu, Co, Ni, and Zn the precipitate is soluble in excess.

**Na<sub>2</sub>HPO<sub>4</sub>** precipitates all the metals except the alkalis as phosphates, Hg as basic chlorid, and Sb as oxid.

**Na<sub>2</sub>CO<sub>3</sub>** precipitates all the metals except the alkalis as follows: Ag<sub>2</sub>CO<sub>3</sub>, Hg<sub>2</sub>CO<sub>3</sub>, CdCO<sub>3</sub>, FeCO<sub>3</sub>, MnCO<sub>3</sub>, BaCO<sub>3</sub>, SrCO<sub>3</sub>, CaCO<sub>3</sub>, Fe(OH)<sub>3</sub>, Al(OH)<sub>3</sub>, Cr(OH)<sub>3</sub>, Sn(OH)<sub>2</sub>, H<sub>2</sub>SnO<sub>3</sub>, Sb<sub>2</sub>O<sub>3</sub>, Hg<sub>2</sub>OCl<sub>2</sub>, H<sub>3</sub>SbO<sub>4</sub>, and basic carbonates of Pb, Cu, Zn, Co, and Ni.

**H<sub>2</sub>SO<sub>4</sub>** precipitates PbSO<sub>4</sub>, BaSO<sub>4</sub>, SrSO<sub>4</sub>, CaSO<sub>4</sub> (incompletely), and HgSO<sub>4</sub> (incompletely).

**NaOH** precipitates Ag<sub>2</sub>O, Hg<sub>2</sub>O, H<sub>2</sub>O, Cu(OH)<sub>2</sub>, Cd(OH)<sub>2</sub>, BiO(OH), SbO(OH)<sub>3</sub>, Sn(OH)<sub>2</sub>, SnO(OH)<sub>2</sub>, Fe(OH)<sub>3</sub>, Fe(OH)<sub>2</sub>, Ni(OH)<sub>2</sub>, Co(OH)<sub>2</sub>, Mn(OH)<sub>2</sub>, Ba(OH)<sub>2</sub> (incompletely), Sr(OH)<sub>2</sub> (incompletely), Ca(OH)<sub>2</sub> (incompletely), Mg(OH)<sub>2</sub>, and the following which are soluble in excess: Pb(OH)<sub>2</sub>, Sb<sub>2</sub>O<sub>3</sub>, SbO(OH)<sub>3</sub>, Sn(OH)<sub>2</sub>, SnO(OH)<sub>2</sub>, Al(OH)<sub>3</sub>, Cr(OH)<sub>3</sub>, Zn(OH)<sub>2</sub>.

**NH<sub>4</sub>C<sub>2</sub>O<sub>4</sub>** precipitates oxalates of all the metals except the alkalis from alkaline solutions.

### *B. Wet Tests for Acids*

**With BaCl<sub>2</sub> as a reagent.**

A white ppt. insoluble in HCl indicates SO<sub>4</sub>.

A white ppt. soluble in HCl, but insoluble in acetic acid indicates F.

A yellow ppt. soluble in HCl but insoluble in acetic acid indicates  $\text{CrO}_4$ .

A white ppt. soluble in HCl and in acetic acid indicates  $\text{BO}_2$  or  $\text{B}_4\text{O}_7$ ,  $\text{PO}_4$ ,  $\text{CO}_3$ , or  $\text{AsO}_4$ .

**With  $\text{AgNO}_3$  as a reagent.**

A yellow ppt. soluble in  $\text{HNO}_3$  indicates  $\text{PO}_4$ .

A red or red-brown ppt. soluble in  $\text{HNO}_3$  indicates  $\text{AsO}_4$  or  $\text{CrO}_4$ .

A white ppt. soluble in  $\text{HNO}_3$  indicates  $\text{BO}_2$  or  $\text{B}_4\text{O}_7$ .

A white ppt. insoluble in  $\text{HNO}_3$  indicates Cl.

A black ppt. soluble in  $\text{HNO}_3$  indicates S.

**XVII. Preparation of Solution.**

Water is the first solvent used, and after that either hydrochloric or nitric acids. For some minerals HCl is the best solvent and for some  $\text{HNO}_3$  is the best so that it is well to try a small quantity of the mineral with each of these solvents to determine which is the better. For sulfids  $\text{HNO}_3$  is the best solvent, but if Pb, Sb, and Sn are present white residues are formed. HCl will precipitate chlorids of Ag, Pb, and Hg. If the substance is insoluble in both  $\text{HNO}_3$  and HCl it may be soluble in aqua regia (1 part  $\text{HNO}_3$  + 3 parts HCl).

Many minerals, especially silicates, are insoluble in aqua regia, and require fusion with  $\text{Na}_2\text{CO}_3$  on platinum foil or in a porcelain crucible. A water solution of the fusion will generally contain sodium salts of various acids while an acid solution of the residue will generally contain the metals.

The following minerals are not decomposed by  $\text{Na}_2\text{CO}_3$  and require fusion with KOH in a nickel or silver crucible; corundum,  $\text{Al}_2\text{O}_3$ ; cassiterite,  $\text{SnO}_2$ ; and rutile,  $\text{TiO}_2$ .

## XVIII. Qualitative Scheme (for the more common elements).

- |                           |   |   |
|---------------------------|---|---|
| HCl Group.                | { | 1. Add cold dilute HCl in excess. Ppt. 2. Filtrate 6.<br>2. Wash ppt. with hot water on filter-paper. Residue 3. Filtrate 5.<br>3. Add $\text{NH}_4\text{OH}$ to residue drop by drop. A blackening indicates <b>Hg</b> .<br>Divide filtrate into two portions 4 and 5.<br>4. Acidify filtrate with $\text{HNO}_3$ . A white ppt. indicates <b>Ag</b> .<br>5. Test filtrate with $\text{K}_2\text{CrO}_4$ . A yellow ppt. indicates <b>Pb</b> .   |
| H <sub>2</sub> S Group.   | { | 6. Pass $\text{H}_2\text{S}$ into warm, slightly acid solution. Ppt. 7. Filtrate 16.<br>7. Digest ppt. with $(\text{NH}_4)_2\text{S}$ . Filter. Residue 8. Filtrate 13.<br>8. Digest residue with hot dilute $\text{HNO}_3$ . Filter. Residue 9.<br>Filtrate 10.<br>9. Dissolve residue in aqua regia. Boil off Cl. A ppt. with $\text{SnCl}_2$ indicates <b>Hg</b> .<br>10. Add a little conc. $\text{H}_2\text{SO}_4$ and drive off excess. A white ppt. indicates <b>Pb</b> . Filtrate 11.<br>11. Add $\text{NH}_4\text{OH}$ in excess to filtrate. A white ppt. indicates <b>Bi</b> .<br>Filtrate 12.<br>12. A blue filtrate indicates <b>Cu</b> . Add $\text{KCN}$ until blue color disappears. Then pass $\text{H}_2\text{S}$ . A yellow ppt. indicates <b>Cd</b> .<br>13. Add dilute HCl to filtrate. Heat ppt. formed with conc. HCl. A residue indicates <b>As</b> . Filtrate 14.<br>14. Into the dilute solution, heated to almost boiling, pass $\text{H}_2\text{S}$ . An orange red ppt. indicates <b>Sb</b> . Filtrate 15.<br>15. Into the cool diluted filtrate pass $\text{H}_2\text{S}$ . A yellow ppt. indicates <b>Sn</b> . |
| NH <sub>4</sub> OH Group. | { | 16. Boil off $\text{H}_2\text{S}$ , add a few drops of $\text{HNO}_3$ . Add $\text{NH}_4\text{Cl}$ and $\text{NH}_4\text{OH}$ . Ppt. 17. Filtrate 22.<br>17. Dissolve ppt. in least possible amount of HCl. Add 50% alcohol and dilute $\text{H}_2\text{SO}_4$ . A crystalline ppt. indicates <b>Ca</b> . Filtrate 18.<br>18. Boil off the alcohol, make filtrate alkaline with $\text{NH}_4\text{OH}$ . Ppt. 19. Reject filtrate.<br>19. Fuse ppt. with $\text{Na}_2\text{CO}_3$ and $\text{NaNO}_3$ on platinum foil. A bluish-green mass indicates <b>Mn</b> . Digest fused mass in hot water and filter. Residue indicates <b>Fe</b> . Divide filtrate into two portions, 20 and 21.<br>20. A yellow filtrate giving red ppt. with $\text{AgNO}_3$ indicates <b>Cr</b> .<br>21. Acidify with HCl. Add solid $\text{NH}_4\text{Cl}$ and boil. A ppt. indicates <b>Al</b> .   |

- |  |   |  |
|--|---|--|
| (NH <sub>4</sub> ) <sub>2</sub> S Group.   | { | 22. Into the warm alkaline filtrate pass H <sub>2</sub> S. Ppt. 23. Filtrate 29.   |
|  |   | 23. Wash ppt. on filter with cold dilute (1:10) HCl. Residue 24. Filtrate 26.  |
|  |   | 24. Dissolve residue in aqua regia. Evaporate to dryness, add a little water and make strongly basic with NaOH. Add tartaric acid but not enough to make the solution acid. Heat slightly and pass H <sub>2</sub> S. A ppt. indicates Co. Filtrate 25. |
|  |   | 25. Acidify filtrate with HCl. A ppt. indicates Ni.  |
|  |   | 26. Boil filtrate to remove H <sub>2</sub> S. Add KOH in excess. Ppt. 27. Filtrate 28.   |
|  |   | 27. Fuse ppt. with Na <sub>2</sub> CO <sub>3</sub> . A bluish-green mass indicates Mn.   |
|  |   | 28. Add H <sub>2</sub> S to the filtrate and heat. A white ppt. indicates Zn.  |
|  |   | (NH <sub>4</sub> ) <sub>2</sub> CO <sub>3</sub> Group.   |
| 30. Dissolve ppt. in hot dilute acetic acid and add K <sub>2</sub> CrO <sub>4</sub> . A yellow ppt. indicates Ba. Filtrate 31. |   |  |
| 31. Add NH <sub>4</sub> OH and alcohol. A yellow ppt. indicates Sr. Filtrate 32.   |   |  |
| 32. Dilute and add (NH <sub>4</sub> ) <sub>2</sub> C <sub>2</sub> O <sub>4</sub> . A white ppt. indicates Ca. Filtrate 33.     |   |  |
| 33. Add NH <sub>4</sub> OH and Na <sub>2</sub> HPO <sub>4</sub> . A white ppt. indicates Mg.                                   |   |  |
| Alkali Group.  | { | 34. Evaporate filtrate to dryness. Ignite to drive off ammonium salts. Add NaOH and Na <sub>2</sub> HPO <sub>4</sub> . Heat and add alcohol. A white ppt. indicates Li. Filtrate 35.   |
|  |   | 35. To the filtrate add Na <sub>2</sub> Co(NO <sub>2</sub> ) <sub>6</sub> . A yellow ppt. indicates K.   |
|  |   | Note.—The original substance must be tested for Na and NH <sub>4</sub> .   |

## 11. SELECT BLOWPIPE AND WET TESTS

### Aluminum, Al.

1. Infusible aluminum minerals (also zinc silicates) ignited before and after adding cobalt nitrate solution give an intense blue color. Fusible minerals may give a blue cobalt glass whether aluminum is present or not.

2. Ammonia gives a white gelatinous precipitate, Al(OH)<sub>3</sub>, in solutions containing aluminum. Iron hydroxid, chromium hydroxid, calcium phosphate, calcium borate, and calcium fluorid are also precipitated by NH<sub>4</sub>OH along with Al(OH)<sub>3</sub>.

**Ammonium,  $\text{NH}_4$ .**

1. Ammonium salts heated in the closed tube with KOH, NaOH, or CaO (made by heating calcite,  $\text{CaCO}_3$ ) give the characteristic ammonia odor.

**Antimony, Sb.**

1. Antimony minerals heated on the charcoal in O.F. give a white coating ( $\text{Sb}_2\text{O}_3$ ) near the assay and dense white fumes without odor.

2. With bismuth flux on plaster antimony compounds give a peach-red coating or an orange coating stippled with peach-red.

3. In the open tube antimony minerals give a non-volatile, amorphous, white sublimate ( $\text{Sb}_2\text{O}_3$ ) on the under side of the tube.

4. Concentrated  $\text{HNO}_3$  oxidizes antimony sulfids and sulfosalts to  $\text{HSbO}_3$ , a white precipitate soluble in KOH.

**Arsenic, As.***A. Compounds without Oxygen*

1. On charcoal most arsenic minerals give a white volatile coating ( $\text{As}_2\text{O}_3$ ) far from the assay and fumes with characteristic odor of arsine ( $\text{AsH}_3$ ).

2. In open tube minute, brilliant, colorless crystals ( $\text{As}_2\text{O}_3$ ).

3. In closed tube a black mirror of arsenic.

4.  $\text{H}_2\text{S}$  precipitates yellow  $\text{As}_2\text{S}_3$ , which is soluble in  $(\text{NH}_4)_2\text{S}_x$ , but insoluble in concentrated HCl.

*B. Arsenates*

5. Arsenates heated intensely in closed tube with charcoal give a black metallic mirror.

6. Nitric acid solutions of arsenates give a yellow precipitate with  $(\text{NH}_4)_2\text{MoO}_4$  when heated to boiling.

**Barium, Ba.**

1. Yellowish-green flame (not made blue by HCl).

2. Dilute  $\text{H}_2\text{SO}_4$  precipitates white  $\text{BaSO}_4$  from dilute solutions.

3.  $\text{K}_2\text{CrO}_4$  or  $\text{K}_2\text{Cr}_2\text{O}_7$  gives a yellow precipitate.
4.  $(\text{NH}_4)_2\text{CO}_3$  or  $(\text{NH}_4)_2\text{C}_2\text{O}_4$  gives a white precipitate soluble in acids. (Sr and Ca also).

### **Beryllium, Be.**

1.  $\text{Be}(\text{OH})_2$  is precipitated along with  $\text{Al}(\text{OH})_3$  by  $\text{NH}_4\text{OH}$ . The precipitate is dissolved in dilute  $\text{HCl}$  and the solution evaporated nearly to dryness. A little water is added, and also  $\text{KOH}$  in amount sufficient to dissolve the precipitate which forms at first. The solution is diluted and boiled when  $\text{Be}(\text{OH})_2$  separates out. (Brush-Penfield).

### **Bismuth, Bi.**

1. With bismuth flux on plaster a purplish-chocolate coating with underlying scarlet.
2. With soda on charcoal R.F., a metallic button brittle on the edges and also a yellow sublimate.
3. To a nitric acid solution from which the excess of acid has been evaporated  $\text{HCl}$  is added. On dilution with water, a white precipitate,  $\text{BiOCl}$ , is formed.

### **Boron, B.**

1. Borates give a green flame especially if moistened with  $\text{H}_2\text{SO}_4$ . Silicates containing boron give a green flame when heated with boracic acid flux (3 parts  $\text{KHSO}_4$  to 1 part powdered fluorite,  $\text{CaF}_2$ ).  $\text{BF}_3$  is formed.
2. Alcohol added to a solution of a borate will burn with a green flame.
3. Turmeric paper moistened with a  $\text{HCl}$  solution of a borate, and dried carefully on the outside of the test-tube containing the boiling solution becomes reddish-brown. This color is changed to black by  $\text{NH}_4\text{OH}$ . It is well to run a blank test at the same time.

### **Calcium, Ca.**

1. The microchemical gypsum test is the most satisfactory test for calcium. A drop of solution containing calcium is placed



on a glass slip and alongside of it a drop of dilute  $\text{H}_2\text{SO}_4$ . The two drops are brought into contact at some point. In a few minutes time small crystals of  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  (gypsum) make their appearance. (See Fig. 387.)

2. In a rather concentrated solution dilute  $\text{H}_2\text{SO}_4$  precipitates crystalline  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ . The addition of alcohol makes a more complete precipitation.

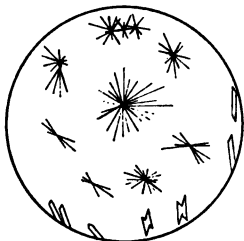


FIG. 387.  
Microchemical gypsum.

3. Yellowish-red flame with  $\text{HCl}$ .

4.  $(\text{NH}_4)_2\text{C}_2\text{O}_4$  or  $(\text{NH}_4)_2\text{CO}_3$  gives a white precipitate soluble in acids, as do also Ba and Sr. Ba gives a yellow precipitate with  $\text{K}_2\text{CrO}_4$ .  $\text{Ca}(\text{NO}_3)_2$  is soluble in ether-alcohol, while  $\text{Sr}(\text{NO}_3)_2$  is insoluble.

5. Calcium borates, fluorids, and phosphates are all precipitated from acid solutions on the addition of  $\text{NH}_4\text{OH}$ .

### Carbon, C.

1. Carbonates effervesce in dilute acids (some in the cold, others only upon heating) with the evolution of a colorless, odorless gas which gives a white precipitate with  $\text{Ba}(\text{OH})_2$  or lime-water.

2. Citric acid, a solid, serves as a convenient field reagent. Carbonates effervesce in a water solution of citric (or tartaric) acid.

3. Hydrocarbons, such as asphaltum, albertite, coal, etc., which are not minerals, properly speaking, heated in the closed tube give oils and tar-like substances.

### Chlorin, Cl.

1. To a  $\text{NaPO}_3$  bead saturated with  $\text{CuO}$  (or malachite) a little of the powdered substance is added. On heating, an intense azure-blue flame is obtained.

2. In chlorid solutions  $\text{AgNO}_3$  gives a white curdy precipitate which is soluble in  $\text{NH}_4\text{OH}$ .

### Chromium, Cr.

1. The borax and sodium metaphosphate beads are emerald green in both O.F. and R.F.
2. The sodium carbonate bead is yellow in O.F.  $\text{KNO}_3$  or  $\text{NaNO}_3$  helps the reaction.
3. Chromate solutions give a dark red precipitate with  $\text{AgNO}_3$ .

### Cobalt, Co.

1. The borax and sodium metaphosphate beads are deep blue in both O.F. and R.F. This is a very delicate test.
2. Heated on charcoal in R.F., cobalt compounds become magnetic.

### Copper, Cu.

1. Green flame made azure-blue with  $\text{HCl}$ .
2. Borax and sodium metaphosphate beads are blue in O.F. and opaque red in R.F. In the presence of iron, the O.F. bead is green or bluish-green.
3. On charcoal with soda in R.F. and also with  $\text{NaPO}_3$  and metallic tin on charcoal, metallic copper (malleable) is obtained.
4. Solutions of copper minerals are blue (green in the presence of iron).  $\text{NH}_4\text{OH}$  produces a deep blue coloration.
5. Copper solutions touched to a bright surface of iron, such as knife-blade or hammer, give a coating of metallic copper.

### Fluorin, F.

1. Fluorids are soluble in concentrated  $\text{H}_2\text{SO}_4$  with evolution of  $\text{HF}$  which etches glass. A lead dish, or watch-glass coated with paraffin, should be used.
2. Fluorin compounds heated in a closed tube with 4 parts of  $\text{NaPO}_3$  will etch glass and deposit a ring of  $\text{SiO}_2$ , which cannot be washed off with water.
3. Fluorin compounds heated with concentrated  $\text{H}_2\text{SO}_4$  and powdered silica give fumes which condense on moistened black paper. (Browning.)

4. Fluorids give a momentary green flame when heated with borax and  $\text{KHSO}_4$ . This flame is due to the formation of volatile  $\text{BF}_3$ .

### Gold, Au.

1. With soda on charcoal gold compounds give a malleable yellow button.

2. Gold may be identified in some of its rich ores by panning and washing away light quartz, rock, etc. Mercury is added to the concentrates. By grinding in a mortar an amalgam of gold is obtained. This may be heated on charcoal or in a closed tube and the mercury driven off. The residue is heated with a little borax on charcoal and a globule of gold obtained.

### Hydrogen, H.

1. Minerals with so-called water of crystallization give off water when heated in a closed tube at a comparatively low temperature ( $100\text{--}150^\circ\text{C}$ ). With hydrous sulphates of iron, copper, and aluminum the water has an acid reaction which is due to the  $\text{SO}_3$  given off.

2. Acid salts and basic salts give off water at comparatively high temperatures (usually above  $150^\circ\text{C}$ ).

### Iron, Fe.

1. On charcoal R.F., especially with soda, iron minerals become magnetic. (Also Co and Ni.)

2. In O.F. the borax bead is amber colored and in R.F., bottle green.

3.  $\text{NH}_4\text{OH}$  precipitates brownish-red  $\text{Fe}(\text{OH})_3$ . A few drops of  $\text{HNO}_3$  should always be added to the solution to insure oxidation of the iron.

4. To detect state of iron, a borax bead made blue with  $\text{CuO}$  (or malachite) is changed to opaque red by a ferrous compound and to green by a ferric compound. (Use a neutral flame.)

5. To detect the state of iron in insoluble silicates, fuse pow-

dered mineral with a large excess of borax in a test-tube. Break tube and dissolve contents in HCl. Test the solution with  $K_4Fe(CN)_6$  (ferric compounds give a blue precipitate) and with  $K_3Fe(CN)_6$  (ferrous compounds give a blue precipitate).

#### **Lead, Pb.**

1. On charcoal with ~~soda~~ in R.F. a malleable button of lead and a yellow coating of  $PbO$ .  $PbS$  also gives a white coating of  $PbSO_4$ .

2. On plaster with bismuth flux, a lemon-yellow coating.

3. From solutions containing lead, HCl precipitates  $PbCl_2$ , which is soluble in hot water, but recrystallizes on cooling the solution as white acicular crystals with adamantine luster.

#### **Lithium, Li.**

1. A purplish-red flame, most intense at first.

2. For separation from the other alkalis, see item 34, page 195.

#### **Magnesium, Mg.**

1. In the presence of  $NH_4OH$  and  $NH_4Cl$ ,  $Na_2HPO_4$  precipitates  $NH_4MgPO_4 \cdot 6H_2O$ , which forms slowly. Other metals (except alkalis) must be absent as they also give precipitates.

2. White magnesium compounds give a pink color when ignited with cobalt nitrate solution. (This test is not very satisfactory).

#### **Manganese, Mn.**

1. Bluish-green ~~soda~~ bead (a very delicate test).

2. The borax or  $NaPO_3$  bead is amethyst colored in O.F. and colorless in R.F.

3. With HCl manganese dioxids give off chlorine, a gas recognized by its penetrating odor.

#### **Mercury, Hg.**

1. In closed tube with *dry* soda gives globules of mercury.

2. On plaster with bismuth flux a scarlet sublimate when

gently heated. If overheated, the sublimate is dark greenish-yellow.

3. Most mercury compounds rubbed on a copper coin with HCl give a white amalgam.

### **Molybdenum, Mo.**

1.  $\text{NaPO}_3$  bead is green in R.F., but colorless in O.F. The R.F. beads dissolved in HCl with tin give a brown solution.

2.  $\text{Na}_2\text{HPO}_4$  gives a yellow precipitate with nitric acid solutions of molybdenum compounds.

### **Nickel, Ni.**

1. The borax bead in O.F. is violet when hot, reddish-brown cold, while in R.F. the bead is turbid gray.

2. With nickel solutions NaOH gives a pale green precipitate which is insoluble in excess. With  $\text{NH}_4\text{OH}$  a precipitate is formed which is soluble in excess to a pale blue solution (fainter than copper).

3. The separation of nickel and cobalt may be effected thus: To a solution free from  $\text{NH}_4\text{OH}$  add NaOH until strongly basic. Then add tartaric acid, but not enough to make the solution acid. Heat slightly and pass  $\text{H}_2\text{S}$ . The cobalt will be precipitated, while the nickel remains in solution. After filtering, the nickel may be precipitated from the filtrate by acidifying with HCl.

### **Niobium, Nb.**

1. When fused with borax and then dissolved in HCl, the addition of metallic tin gives a deep blue solution similar to that obtained for tungsten.

### **Nitrogen, N.**

1. In closed tube with  $\text{KHSO}_4$  nitrates give brown-red fumes of  $\text{NO}_2$ .

2. A concentrated solution of  $\text{FeSO}_4$  added to a solution of a nitrate in concentrated  $\text{H}_2\text{SO}_4$  gives a brown ring.

**Oxygen, O.**

No direct tests for oxygen are easily made. The higher oxides of manganese dissolve in HCl with the evolution of Cl.

**Phosphorus, P.**

1. An excess of  $(\text{NH}_4)_2\text{MoO}_4$  added to a nitric acid solution of a phosphate gives a yellow precipitate which is soluble in  $\text{NH}_4\text{OH}$ . The solution should be only slightly heated, for arsenates give a similar precipitate on boiling.

2. Bluish-green flame when moistened with  $\text{H}_2\text{SO}_4$ .

**Platinum, Pt.**

1. Insoluble in any single acid, but soluble in aqua regia. In rather concentrated, slightly acid solutions KCl gives a yellow precipitate,  $\text{K}_2\text{PtCl}_6$ , insoluble in alcohol.

**Potassium, K.**

1. Violet flame, masked by sodium, but visible through a blue glass.

2. Sodium cobaltic nitrite,  $\text{Na}_3\text{Co}(\text{NO}_2)_6$ , (see p. 180), gives a yellow precipitate insoluble in alcohol.

3. With  $\text{H}_2\text{PtCl}_6$  solution gives a yellow crystalline precipitate insoluble in alcohol.

**Silicon, Si.**

1. In the  $\text{NaPO}_3$  bead silica and the silicates are only partially dissolved, leaving a translucent mass or skeleton of  $\text{SiO}_2$ .

2. With a small amount of soda, silica effervesces and forms a clear mass. The equation is:  $\text{Na}_2\text{CO}_3 + \text{SiO}_2 = \text{Na}_2\text{SiO}_3 + \text{CO}_2$ .

3. Some silicates dissolve in  $\text{HNO}_3$  or HCl and on evaporation leave a gelatinous mass or a slime of silicic acid.

4. For insoluble silicates a soda fusion must be made. The finely powdered mineral is fused on platinum foil, or a spiral loop of platinum wire, with three parts of soda. The fused mass is dissolved in dilute  $\text{HNO}_3$  and carefully evaporated just to dryness. Add dilute HCl and boil. Filter off the insoluble silica.

The filtrate contains the bases, which are commonly Al, Fe, Ca, and Mg. The following is a scheme of separation:

Add $\text{NH}_4\text{OH}$ and $\text{NH}_4\text{Cl}$ (boiling)	$\text{Fe}(\text{OH})_3, \text{Al}(\text{OH})_3, \text{Al}(\text{OH})_3$ is soluble in $\text{KOH}$ .	
	Add $(\text{NH}_4)_2\text{C}_2\text{O}_4$ (hot)	$\text{CaC}_2\text{O}_4$
	Add $\text{Na}_2\text{HPO}_4$ (cold)	$\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$

5. For the detection of alkalis in silicates the *very finely* powdered substance is intimately mixed with five parts of  $\text{CaCO}_3$  and one part of  $\text{NH}_4\text{Cl}$  and fused for some time on platinum foil. The sintered mass is digested in hot water and filtered.  $\text{NH}_4\text{OH}$  and  $(\text{NH}_4)_2\text{CO}_3$  are added to the filtrate. The precipitate is filtered off and the filtrate evaporated to dryness. The residue is ignited until all the ammonium salts are volatilized. Dissolve the residue in a little water. Add  $\text{H}_2\text{PtCl}_6$  and alcohol. A yellow precipitate indicates K. Evaporate filtrate to dryness and test flame for Na.

#### Silver, Ag.

1. With soda on charcoal in R.F., silver minerals yield malleable metallic globules of silver, which may be tested as under 3.

2. For silver cupellation see page 189.

3. Nitric acid solutions of silver minerals on the addition of  $\text{HCl}$  give a white curdy precipitate which changes to violet on exposure to light and is soluble in  $\text{NH}_4\text{OH}$ .

#### Sodium, Na.

1. Intense yellow flame masked by a blue glass. This is a delicate test so that only an intense and prolonged coloration indicates sodium as an essential constituent.

2. Sodium in insoluble silicates may be detected by the method given under Silicon, note 5.

**Strontium, Sr.**

1. Strontium compounds give a crimson flame, especially with HCl.

2. Dilute  $\text{H}_2\text{SO}_4$  gives a white precipitate,  $\text{SrSO}_4$ , with dilute strontium solutions.

**Sulfur, S.***A. Sulfids and Sulfo-salts*

1. The finely powdered substance fused with three parts of soda on a sheet of mica or platinum foil gives a mass which stains a moistened silver coin. Tellurids and selenids give the same test.

2. In the closed tube some sulfids give a yellow sublimate of sulfur.

3. In the open tube sulfids give off  $\text{SO}_2$ , a colorless gas with the odor of burning matches.

4. A few sulfids dissolve in HCl with the evolution of  $\text{H}_2\text{S}$ . (e.g., sphalerite.)

5. Sulfids are oxidized to sulfates by nitric acid with the evolution of brown-red fumes of  $\text{NO}_2$ . The solution may be tested as under 7 below.

*B. Sulfates*

6. A sulfate, powdered and thoroughly mixed with 3 parts of soda and a little charcoal powder, is fused on charcoal in R.F. The fused mass will stain a moistened silver coin. Sulfids give the same test so it is necessary to try the test on mica or platinum first.

7. Sulfate solutions with  $\text{BaCl}_2$ , give a white precipitate which is insoluble in HCl.

8. Sulfate solutions will give microchemical gypsum with a calcium salt (calcite dissolved in HCl is convenient). See Calcium, note 1, page 197.

**Tellurium, Te.**

1. A powdered tellurid added to hot concentrated  $\text{H}_2\text{SO}_4$  gives a fine red-violet coloration.



2. Tellurids give a pale bluish-green flame coloration and a white sublimate on charcoal.

3. On plaster with bismuth flux a purplish sublimate is obtained with tellurids.

### **Tin, Sn.**

1. Tin compounds heated on charcoal in O.F. give a straw-colored coating,  $\text{SnO}_2$ . On addition of  $\text{Co}(\text{NO}_3)_2$  solution and heating in R.F., a bluish-green coloration results.

2. Tin compounds fused on charcoal with soda and a little sulfur in strong R.F. give malleable metallic buttons of tin which are oxidized by  $\text{HNO}_3$  to a white insoluble powder,  $\text{H}_2\text{SnO}_3$ .

### **Titanium, Ti.**

1. The  $\text{NaPO}_3$  bead is violet in R.F. and colorless in O.F.

2. Fused with soda, dissolved in  $\text{HCl}$ , and the solution heated with metallic tin, titanium compounds give a violet colored solution due to the formation of  $\text{TiCl}_3$ . The solution is usually turbid due to the formation of metatitanic acid,  $\text{H}_2\text{TiO}_3$ .

3. To the substance fused with  $\text{KHSO}_4$  a solution of hydrogen peroxide is added when a yellow coloration results. This is a very delicate test.

### **Tungsten, W.**

1. The  $\text{NaPO}_3$  bead is blue in R.F., colorless in O.F. Iron interferes and gives a red bead in R.F.

2.  $\text{NaPO}_3$  beads treated on charcoal in R.F. with tin are dissolved in  $\text{HCl}$  with the addition of metallic tin to a deep blue solution.

3. With soluble tungstates  $\text{HCl}$  gives a yellow residue,  $\text{WO}_3$ , which is soluble in ammonia.

### **Uranium, U.**

1. The  $\text{NaPO}_3$  bead is a fine green in R.F. and yellowish-green in O.F.

Vanadium, V.

Vanadium  
a  
t

at  
Zi

col  
mu



# PART V

## THE DETERMINATION OF MINERALS

### 1. Introduction

Until one has had considerable experience with minerals it is necessary to determine many of them by physical or chemical tests. If there is no clue to the mineral, it is better to use determinative tables than to make tests at random. In this part of the book are six tables to aid in determining minerals by (1) crystal form, (2) structure ~~or~~ cleavage, (3) color, (4) specific gravity, (5) optical tests, and (6) blowpipe and chemical tests. The more common minerals are distinguished by larger type.

In making tests the homogeneity and purity of minerals is important. If possible the impurity should be removed, if not, the effect of the impurity must be taken into account. As physical tests involve little, if any, waste of material, they should be made before the chemical tests. All the tests must, of course, be made on the same kind of material.

The following remarks will help in the use of the tables. It must be emphasized that these or similar tables do not determine a mineral, but simply give one a clue to the determination. The description of the suspected mineral should always be looked up and additional confirmatory tests made.

### 2. Crystal Form

The crystal form is highly characteristic and many minerals may be determined by examination of crystals alone. But as the crystal habit is often variable and as large isolated crystals are comparatively rare, a fairly comprehensive knowledge of crys-

tallography is necessary. The simple reflection goniometer described on page 81 may be used to advantage in determining crystals. It should be noted that isomorphous minerals have nearly identical angles and that for all isometric crystals the angles between corresponding faces are identical. Cleavage observations are of great value in orienting a crystal.

For crystalline aggregates the first half of Table 2 is used.

### 3. Physical Tests

Typical specimens of minerals are most easily recognized by simple physical tests. Of these, cleavage is one of the most satisfactory. Cleavage should be recognized by surfaces with step-like arrangement rather than by cracks through the specimen, as these may be due to other causes.

The second half of Table 2 is a list of minerals with prominent cleavage. The horizontal divisions of Tables 2 and 3 are based upon hardness. The top division includes minerals scratched by the finger-nail, the lower division, those not scratched by the knife, while the middle division includes those scratched by the knife, but not by the finger-nail.

Table 3 is a list of minerals arranged by color (secondarily by hardness). The metallic colors are listed separately. For some minerals the color is characteristic and practically constant. For others there is great variation due to impurities and to isomorphous replacement. Fluorite, for example, is white, colorless, violet, blue, green, pink, yellow, and brown. The minerals with metallic luster are quite constant in color, though it may be concealed by surface tarnish. A fresh fracture should always be used. Metallic minerals are opaque even on the thinnest edges.

The specific gravity is one of the most constant properties of minerals. For pure massive specimens without cleavage it is one of the best means of identification. Table 4 is a list of minerals arranged according to increasing specific gravity. The numbers given represent the average value for pure minerals. In using these tables it is well to allow one or two tenths (for the heavy

minerals even more) on each side of the observed value as replacement or invisible impurities may cause some variation. After some experience one can judge roughly by the "heft" the approximate specific gravity of a mineral if it is not too small. Taking quartz (sp. gr. 2.67) and calcite (sp. gr. 2.72) as standards, gypsum (sp. gr. 2.3) feels light, while topaz (sp. gr. 3.5) feels heavy and barite (sp. gr. 4.5), very heavy.

#### 4. Optical Tests

The determination of minerals by optical tests is at present limited to those that are fairly transparent in thin slices or fragments. But many minerals which are apparently opaque become transparent or translucent when thin. For many non-metallic minerals the optical determinations are easier to make and more satisfactory than blowpipe and chemical determinations. Then besides, some distinctions which are impossible by chemical methods are easy to make with the microscope. For example, the distinctions between quartz and chalcedony, calcite and aragonite, augite and hornblende.

The author's method<sup>1</sup> for optical determinations consists of reducing the mineral to coarse powder by pounding it on an anvil rather than by grinding. The largest fragments that go through a 100-mesh sieve are examined in some liquid such as oil of cloves on the stage of a polarizing microscope, and the shape, color, pleochroism, index of refraction, interference colors, extinction, elongation, twinning, etc., are noted. The Becke test (see page 117) is used for the determination of the index of refraction. The most convenient liquids are oil of cloves,  $n=1.53$ ; bromoform,  $n=1.59$ ;  $\alpha$ -monobromnaphthalin,  $n=1.66$ ; and methylene iodid,  $n=1.74$ . If permanent slides are desired, a solution of Canada balsam in xylol is used. The xylol gradually evaporates, leaving the balsam ( $n=1.54$ ).

The following outline will serve as an introduction to the study of optical mineralogy:

<sup>1</sup> *School of Mines Quarterly*, vol. 27, pp. 340-359, 1906.

epsomite and melanterite (Fig. 523, p. 377), halite (Fig. 427, p. 298), kainite (Fig. 517, p. 374), mirabilite (Fig. 518, p. 375), sal-ammoniac (Fig. 429, p. 299), soda-niter (Fig. 506, p. 365), sylvite (Fig. 428, p. 299), and trona (Fig. 498, p. 350).

### 5. Blowpipe and Chemical Tests

These tests are valuable as confirmatory tests and are often necessary in the case of massive minerals when physical tests fail. Blowpipe tests are satisfactory for most of the ordinary acids and bases. Among the exceptions are tests for calcium, magnesium, aluminum (fusible minerals), and phosphates, wet tests being necessary for the recognition of these elements. One great advantage of the blowpipe tests over wet tests is the difficulty of getting many minerals into solution.

As a last resort it may be necessary to make the regular qualitative separations, and for this reason an outline of a qualitative scheme, especially adapted to minerals, is given on pages 194-5.

For a few minerals nothing short of a quantitative analysis suffices for their determination. In some cases a simple water determination will locate a mineral. For example, a careful water determination of a zeolite (the zeolites are very similar chemically) will greatly aid in its identification. The Penfield method of heating the mineral in a hard glass tube and actually weighing the water given off may be employed.

Table 6 helps one determine a mineral by simple blowpipe and chemical tests. The main divisions are those of the prominent acid radicals. The two large divisions are (A) non-metallic luster and (B) metallic luster, but if the luster is in doubt it may be disregarded, in which case the sulfids of division 7 must be considered with division 8, and the remainder of division 7 with division 9.

Blank forms similar to that given on page 228 are very convenient for reporting the results of determinations. The blank space in the upper right-hand corner is for sketches of crystals, crushed fragments, etc.

**TABLE 1**  
**Minerals Arranged According to Crystal System and Habit**



TAE  
MINERALS ARRANGED ACCORDING

	Monoclinic	Orthorhombic	Pseudo-orthorhombic	Tetragonal	Pseudo-tetragonal
Tabular Habit	AZURITE BIOTITE CHLORITE COLEMANITE GYPSUM HEULANDITE MUSCOVITE ORTHOCASE PHLOGOPITE Spodumene TITANITE Wolframite WOLLASTONITE	ANGLESITE ARSENOPYRITE BARITE CALAMINE CELESTITE CERUSSITE Chrysoberyl Columbite MARCASITE OLIVINE	BIOTITE GYPSUM MUSCOVITE <i>Sclerite</i>	APOPHYLLITE Wulfenite	Bournonite
Pyramidal Habit	DATOLITE TITANITE	ANGLESITE SULFUR	DATOLITE	APOPHYLLITE CASSITERITE CHALCOPYRITE Scheelite VESUVIANITE Wulfenite ZIRCON	
Prismatic Habit	AUGITE Aegirite Borax COLEMANITE DATOLITE DIOPSIDE EPIDOTE GYPSUM HORNBLende ORTHOCASE Spodumene TITANITE TREMOLITE Vivianite WOLLASTONITE	ANDALUSITE ANGLESITE ANHYDRITE BARITE CELESTITE CERUSSITE Enargite Epsomite MANGANITE NATROLITE OLIVINE STAUROLITE STIBNITE TOPAZ	HORNBLende STILBITE TITANITE TREMOLITE	APOPHYLLITE CASSITERITE RUTILE VESUVIANITE WERNERITE ZIRCON	ANDALUS AUGITE DIOPSIDE NATROLITE TOPAZ

LE 1

## TO CRYSTAL SYSTEM AND HABIT

	Hexagonal	Pseudo-hexagonal		Isometric	Pseudo-isometric
	Alunite <i>locally</i> APATITE BERYL Brucite CALCITE CORUNDUM Covellite GRAPHITE HEMATITE ILMENITE Molybdenite	BIOTITE CHALCOGITE CHLORITE Chrysoberyl LEPIDOLITE MUSCOVITE PHLOGOPITE Polybasite PYRRHOTITE Stephanite Trona	Cubic Habit	Argentite Boracite Cerargyrite Cobaltite CUPRITE FLUORITE GALENA HALITE PYRITE Smaltite Sylvite	APOPHYLLITE CALCITE CHABAZITE Cryolite HEMATITE QUARTZ
	CALCITE CHABAZITE CINNABAR CORUNDUM DOLOMITE HEMATITE Proustite Pyrargyrite QUARTZ RHODOCHROSITE SIDERITE Soda Niter	ARAGONITE CERUSSITE Witherite	Octahedral Habit	Boracite CHROMITE <i>(rare)</i> Cobaltite CUPRITE Diamond FLUORITE <i>(rare)</i> Franklinite GALENA GOLD MAGNETITE PYRITE SPHALERITE SPINEL	CALCITE CHALCOPYRITE
ITE	APATITE BERYL CALCITE CINNABAR CORUNDUM Mimetite NEPHELITE Proustite Pyrargyrite Pyromorphite QUARTZ TOURMALINE Vanadinite	ARAGONITE HORNBLLENDE Iolite Strontianite TREMOLITE	Dodecahedral Habit   Trapezohedral Habit  Tetrahedral Habit  Pyritohedral Habit	Boracite CUPRITE GARNET MAGNETITE   ANALCITE GARNET LEUCITE   Boracite SPHALERITE TETRAHEDRITE  Cobaltite PYRITE	CALCITE   CHALCOPYRITE



**TABLE 2**  
**Minerals Arranged According to Structure and Cleavage**  
**(Including Parting)**

TA  
MINERALS AREA

STRUCTURE

*Colloform*

	Fibrous Acicular	Columnar Bladed	Foliated Micaceous	Mammillary Botryoidal Stalactitic	Pisolithic Oolitic
	Brucite GYPSUM STIBNITE PYROLUSITE Vivianite <i>graphite</i>	STIBNITE <i>brucite</i>	Brucite CHLORITE GYPSUM GRAPHITE Molybdenite Orpiment TALC		BAUXITE
Finger Nail	<i>as hydrous</i> ARAGONITE CALCITE CELESTITE CUPRITE MALACHITE MANGANITE Millerite NATROLITE Pectolite SERPENTINE STILBITE Wavellite WOLLASTONITE	ARAGONITE CALCITE <del>Crossite</del> CYANITE Göthite MANGANITE SERPENTINE Strontianite <i>Diopside</i> <i>Calcium</i>	BARITE BIOTITE LEPIDOLITE <i>Margarite</i> MUSCOVITE PHLOGOPITE <i>Diopside</i> <i>Calcium</i>	ARAGONITE Arsenic CALAMINE CALCITE Hydrozincite MALACHITE OPAL SMITHSONITE	ARAGONITE BAUXITE CALCITE HEMATITE LIMONITE <i>Siderite</i>
Knife	ACTINOLITE HEMATITE HORNBLende LIMONITE TOURMALINE TREMOLITE	ACTINOLITE BERYL CYANITE Diaspore EPIDOTE HORNBLende Hübnerite TOURMALINE TREMOLITE VESUVIANITE Wolframite Zoisite	ALBITE HEMATITE	CASSITERITE CHALCEDONY HEMATITE LIMONITE OPAL PREHNITE PSILOMELANE	CHALCEDONY

# BLE 2

IGED ACCORDING TO

ND

## CLEAVAGE (Including Parting.)

One direction	Two directions at right angles <i>(or nearly at)</i>	Two directions at oblique angles	Three directions	Four or more directions
Brucite CHLORITE GRAPHITE GYPSUM Molybdenite Orpiment STIBNITE TALC Vivianite			(a) At right angles  Sylvite  (b) Two at right angles, the third at an oblique angle GYPSUM	
APATITE APOPHYLLITE BIOTITE CELESTITE COLEMANITE CYANITE LEPIDOLITE Margarite MUSCOVITE PHLOGOPITE <i>... ..</i> <i>... ..</i>			(a) At oblique angles <i>diagonal</i> CALCITE DOLOMITE RHODOCHROSITE SIDERITE (b) At right angles Alabandite ANHYDRITE Cryolite GALENA HALITE (c) Two at right angles, the third at an oblique angle BARITE CELESTITE	CALCITE FLUORITE SPHALERITE <i>Alag...</i>
CYANITE Diapsoe DIOPSIDE EPIDOTE Gôthite HEMATITE Spodumene TOPAZ Wolframite	ALBITE AUGITE DIOPSIDE LABRADORITE MICROCLINE OLIGOCLASE ORTHOCLASE RHODONITE Spodumene WERNERITE	ACTINOLITE Amblygonite Enargite HORNBLende TITANITE TREMOLITE		CORUNDUM MAGNETITE WERNERITE

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**TABLE 3**  
**Minerals Arranged According to Color.—Non-metallic**



**TABLE 3. MINERALS ARRANGED**

Red (or pink)	Sp. gr.	Yellow	Sp. gr.	Green	Sp. gr.	Blue	Sp. gr.
Laumontite	2.3	SULFUR	2.0	Garnierite	2.6	Chalcantithite	2.2
BAUXITE	2.5	GYPSUM	2.3	Vivianite	2.6	Vivianite	2.6
Erythrite	2.9	Orpiment	3.4	TALC	2.7		
Realgar	3.5	<i>Cerargyrite</i>		CHLORITE	2.7		
HEMATITE	5.2	<i>hematite</i>		Cerargyrite	5.5		
Finger Nail							
CHABAZITE	2.1	Copiapite	2.1	CHRYSOCOLLA	2.1	Allophane	1.9
CALCITE	2.7	OPAL	2.1	OPAL	2.1	CHRYSOCOLLA	2.1
DOLOMITE	2.8	SERPENTINE	2.5	Wavellite	2.3	Chalcantithite	2.2
LEPIDOLITE	2.8	CALCITE	2.7	SERPENTINE	2.5	Lasurite	2.4
Margarite	3.0	ARAGONITE	2.9	MUSCOVITE	2.9	LEPIDOLITE	2.8
FLUORITE	3.2	FLUORITE	3.2	FLUORITE	3.2	FLUORITE	3.2
APATITE	3.2	TITANITE	3.5	APATITE	3.2	CYANITE	3.6
RHODOCHROSITE	3.5	LIMONITE	3.8	Atacamite	3.7	AZURITE	3.8
SPHALERITE	4.0	SPHALERITE	4.0	Brochantite	3.9	CELESTITE	3.9
HEMATITE	5.2	SMITHSONITE	4.4	MALACHITE	3.9		
Zincite	5.5	BARITE	4.5	Olivinite	4.3	<i>calcite</i>	
Proustite	5.6	Stibiconite	5.2	SMITHSONITE	4.4		
CUPRITE	6.0	Scheelite	6.0	Pyromorphite	6.8		
Crocoite	6.0	Wulfenite	6.7				
Wulfenite	6.7	Mimetite	7.2				
Vanadinite	6.8						
CINNABAR	8.0						
Knife							
Orthoclase	2.6	OPAL	2.1	OPAL	2.1	Sodalite	2.3
QUARTZ	2.6	QUARTZ	2.6	MICROCLINE	2.6	Iolite	2.6
CHALCEDONY	2.6	CHALCEDONY	2.6	QUARTZ	2.6	QUARTZ	2.6
WERNERITE	2.7	BERYL	2.7	CHALCEDONY	2.6	CHALCEDONY	2.6
Chondrodite	3.1	Chondrodite	3.1	OLIGOCLEASE	2.6	BERYL	2.7
TOURMALINE	3.1	VESUVIANITE	3.4	BERYL	2.7	Turquois	2.7
ANDALUSITE	3.2	TOPAZ	3.5	Turquois	2.7	TOURMALINE	3.1
RHODONITE	3.5	WILLEMITE	4.1	PREHNITE	2.9	Glaucophane	3.1
SPINEL	3.6			DATOLITE	2.9	CYANITE	3.6
GARNET	4.0			ACTINOLITE	3.1	CORUNDUM	4.0
CORUNDUM	4.0			HORNBLLENDE	3.2		
WILLEMITE	4.1			TOURMALINE	3.1		
RUTILE	4.2			DIOPSIDE	3.2		
				AUGITE	3.3		
				OLIVINE	3.3		
				EPIDOTE	3.4		
				VESUVIANITE	3.4		
				CYANITE	3.6		
				Chrysoberyl	3.7		
				GARNET	4.0		
				WILLEMITE	4.1		

ACCORDING TO COLOR.—NON-METALLIC

White, colorless or nearly so	Sp. gr.	Gray	Sp. gr.	Brown	Sp. gr.	Black	Sp. gr.
Mirabilite	1.5	GYP SUM	2.3	BAUXITE	2.5	GRAPHITE	2.1
Sal-Ammoniac	1.5	Cerargyrite	5.5	PHLOGOPITE	2.8	WAD	3.0
Ulexite	1.6			WAD	3.0	PYROLUSITE	4.8
Epsomite	1.7			LIMONITE	3.8		
Borax	1.7						
Sylvite <sup>Ka</sup>	2.0						
Sepiolite	2.0						
GYP SUM	2.3						
Soda Niter	2.3						
BRUCITE <sup>1C</sup>	2.4						
Laumontite	2.3						
BAUXITE	2.5						
TALC	2.7						
PYROPHYLLITE	2.8						
Too numerous to mention		CALCITE	2.7	OPAL	2.1	SERPENTINE	2.5
		DOLOMITE	2.8	STILBITE	2.2	CALCITE	2.7
		ANHYDRITE	2.9	HEULANDITE	2.2	BIOTITE	2.9
		Ankerite	3.0	SERPENTINE	2.5	WAD	3.0
		TREMOLITE	3.0	CALCITE	2.7	Alabandite	4.0
		Triphylite	3.5	PHLOGOPITE	2.8	SPHALERITE	4.0
		SIDERITE	3.8	BIOTITE	2.9	MANGANITE	4.3
		Witherite	4.3	WAD	3.0	Pyrrargyrite	5.8
		SMITHSONITE	4.4	APATITE	3.2	Melaconite	5.9
		Scheelite	6.0	TITANITE	3.5		
		ANGLESITE	6.2	LIMONITE	3.8		
				SIDERITE	3.9		
				SPHALERITE	4.0		
				Gothite	4.2		
				BARITE	4.3		
				Monazite	4.5		
				Pyromorphite	5.1		
				Vanadinite	6.8		
					6.8		
OPAL	2.1	QUARTZ	2.6	OPAL	2.1	QUARTZ	2.6
LEUCITE	2.5	CHALCEDONY	2.6	QUARTZ	2.6	CHALCEDONY	2.6
ALBITE	2.6	ORTHOCLASE	2.6	CHALCEDONY	2.6	TOURMALINE	3.1
ORTHOCLASE	2.6	ALBITE	2.6	HORNBLLENDE	3.1	Glaucophane	3.1
MICROCLINE	2.6	OLIGOCLASE	2.6	TOURMALINE	3.1	HORNBLLENDE	3.2
OLIGOCLASE	2.6	NEPHELITE	2.6	Chondrodite	3.1	AUGITE	3.3
QUARTZ	2.6	LABRADORITE	2.7	Sillimanite	3.2	Aegirite	3.5
CHALCEDONY	2.6	WERNERITE	2.7	ENSTATITE	3.3	SPINEL	3.6
NEPHELITE	2.6	TREMOLITE	3.0	(Diallage,	3.3	GARNET	3.8
BERYL	2.7	Spodumene	3.1	Axinite	3.3	LIMONITE	3.8
LABRADORITE	2.7	Lawsonite	3.1	VESUVIANITE	3.4	Allanite	3.9
WERNERITE	2.7	ANDALUSITE	3.2	STAUROLITE	3.7	PSILOMELANE	4.2
Boracite	2.9	Sillimanite	3.2	LIMONITE	3.8	RUTILE	4.2
DATOLITE	2.9	Zoisite	3.3	CORUNDUM	4.0	Columbite	5.6
PREHNITE	2.9	CORUNDUM	4.0	GARNET	4.0	CASSITERITE	7.0
Amblygonite	3.0			RUTILE	4.2		
TREMOLITE	3.0			ZIRCON	4.7		
Lawsonite	3.1			CASSITERITE	7.0		
ANDALUSITE	3.1						
Spodumene	3.2						
DIOPSIDE	3.2						
Diopside	3.4						
TOPAZ	3.5						
Diamond	3.5						

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**TABLE 3.—Continued.**  
**MINERALS ARRANGED ACCORDING TO COLOR.—METALLIC** *subgroup*

Metallic, black to dark gray	Sp. gr.	Metallic white to light gray	Sp. gr.	Metallic brass, bronze, red	Sp. gr.
GRAPHITE	2.1	STIBNITE	4.5	Bismuth	9.8
STIBNITE	4.5	Molybdenite	4.7		
Molybdenite	4.7	Bismuthinite	6.4		
PYROLUSITE	4.8	Sylvanite	8.0		
Jamesonite	5.7	Bismuth	9.8		
Polybasite	6.1	Mercury	13.6		
Bismuthinite	6.4				
Argentite	7.3				
<b>Finger Nail</b>					
SPHALERITE	4.0	Arsenic	5.7	CHALCOPYRITE	4.2
Alabandite	4.0	Antimony	6.6	Stannite	4.5
MANGANITE	4.3	Iron	7.5	PYRRHOTITE	4.6
Enargite	4.4	Bismuth	9.8	BORNITE	5.2
Stannite	4.5	SILVER	10.5	Millerite	5.5
TETRAHEDRITE	4.7	Platinum	15 to 19	CUPRITE	6.0
CHALCOCITE	5.7	<i>Gold</i>		Nickelite	7.5
<i>Arsenic</i> Bournonite	5.8			COPPER	8.8
Melaconite	5.8			Calaverite	9.0
Pyrargyrite	5.8			Bismuth	9.8
Stephanite	6.2			GOLD	15 to 19
<i>Gold</i> <i>Gold</i> <i>Pyrrhotite</i>					
<b>Knife</b>					
LIMONITE	3.8	ARSENOPYRITE	6.0	MARCASITE	4.9
Allanite	3.9	Smaltite	6.2	PYRITE	5.0
PSILOMELANE	4.2	Löllingite	7.1	Cobaltite	6.1
RUTILE	4.2			<i>for 11.64</i>	
CHROMITE	4.4				
ILMENITE	4.7				
MAGNETITE	5.1				
Franklinite	5.1				
HEMATITE	5.2				
Columbite	5.6				
CASSITERITE	7.0				
Wolframite	7.4				
Uraninite	9.0				

where?

BLANK FORM FOR REPORTING MINERALS

Date..... No..... Name.....

Form .....

Cleavage .....

Luster and Color .....

Hardness .....

Streak.....

Spec. Grav. ....

Other characters .....

Associates..... Mineral suspected.....

Optical characters of crushed fragments and cleavages.....

.....

Fusibility .....

Flame coloration .....

Closed tube .....

Open tube.....

On coal alone.....

On coal with soda .....

Borax bead.....

NaPO<sub>3</sub> bead .....

Solubility.....

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Wet tests .....

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Miscellaneous tests .....

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Division in scheme .....

Summary of important characters .....

..... Mineral .....

**TABLE 4**  
**Minerals Arranged According to Specific Gravity**

TABLE 4. MINERALS ARRANGED

1.5 Mirabilite Sal-ammoniac	2.6 ALBITE Alunite CHALCEDONY <del>Torite</del> Kaolinite MICROCLINE ORTHOCLASE NEPHELINE OLIGOCASE QUARTZ Vivianite	3.2 APATITE DIOPSIDE FLUORITE HORNBLende Sillimanite <del>Zeolite</del>
1.6 Carnallite Ulexite		3.3 AUGITE Axinite <del>Chalcophane</del> ENSTATITE OLIVINE
1.7 Borax Epsomite		
1.9 Allophane Melanterite	2.7 <del>Albite</del> BERYL CALCITE LABRADORITE <del>Pectolite</del> TALC Turquoise WERNERITE	3.4 CALAMINE <del>Diaspore</del> EPIDOTE Hypersthene VESUVIANITE
2.0 Sepiolite SULFUR Sylvite		
2.1 CHABAZITE CHRYSOCOLLA Copiapite GRAPHITE HALITE Hydromagnesite Kainite OPAL STILBITE TRONA	2.8 CHLORITE DOLOMITE LEPIDOLITE MUSCOVITE Pyrophyllite PHLOGOPITE WOLLASTONITE	3.5 <del>Aegirite</del> Diamond Orpiment <del>Realgar</del> RHODOCHROSITE TITANITE TOPAZ <del>Triphylite</del>
2.2 ANALCITE Chalcanthite HEULANDITE NATROLITE	2.9 ANHYDRITE ARAGONITE BIOTITE Boracite Erythrite DATOLITE PREHNITE	3.6 CYANITE GARNET RHODONITE SPINEL
2.3 APOPHYLLITE GYPSUM Laumontite Sodalite Soda-Niter Wavellite	3.0 Amblygonite Ankerite Cryolite Margarite TREMOLITE WAD	3.7 <del>Atacamite</del> <del>Chrysoberyl</del> <del>Hydrozincite</del> STAUROLITE Strontianite
2.4 Brucite COLEMANITE Lasurite	3.1 ANDALUSITE ACTINOLITE Chondrodite Glaucoophane Lawsonite MAGNESITE Spodumene TOURMALINE	3.8 AZURITE GARNET LIMONITE SIDERITE
2.5 BAUXITE Garnierite LEUCITE SERPENTINE		3.9 <del>Allanite</del> Brochantite CELESTITE MALACHITE

*Under discussion of properties of minerals*

# ACCORDING TO SPECIFIC GRAVITY


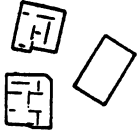

4.0 <del>Chalcandite</del> CORUNDUM GARNET SPHALERITE	5.2 HEMATITE Stibiconite	6.8 Pyromorphite Vanadinite
4.1 <del>Willemite</del> WILLEMITE	5.3	6.9
4.2 CHALCOPYRITE PSILOMELANE RUTILE	5.4	7.0 CASSITERITE
4.3 Gothite MANGANITE <del>Olivanite</del> <i>in y</i> Witherite	5.5 Cerargyrite <del>Millerite</del> <del>Zincite</del>	7.1 <del>Tellingite</del>
4.4 CHROMITE Enargite SMITHSONITE	5.6 Columbite <del>Proustite</del>	7.2 <del>Hebeserite</del> Mimetite
4.5 BARITE <del>Stannite</del> <i>in y</i> STIBNITE	5.7 <del>Arsenic</del> CHALCOCITE Jamesonite	7.3 Argentite
4.6 Covellite PYRRHOTITE ZIRCON	5.8 <del>Bournonite</del> <del>Pyrargyrite</del> <del>Melaconite</del>	7.4 <del>Niocolite</del> Wolframite
4.7 ILMENITE <i>in y</i> Molybdenite TETRAHEDRITE	5.9	7.5 GALENA Iron
4.8 <del>Haussmannite</del> PYROLUSITE <i>in y</i>	6.0 ARSENOPYRITE CUPRITE <del>Crocoite</del> Scheelite	8.0 CINNABAR Sylvanite
4.9 MARCASITE	6.1 <del>Cobaltite</del> Polybasite	8.8 Calaverite COPPER
5.0 PYRITE	6.2 Smaltite Stephanite	9.0 Uraninite
5.1 BORNITE Franklinite MAGNETITE <del>Monsite</del>	6.3 ANGLESITE	9.8 Bismuth
	6.4 Bismuthinite	10.5 SILVER
	6.5 CERUSSITE	13.6 Mercury
	6.6 <del>Antimony</del>	15 to 19 GOLD
	6.7 Wulfenite	Platinum









**Table 5**  
**Minerals Arranged According to Optical Tests**

TABLE 5. MINERALS ARRANG

		Triangular  FIG. 388.	Rectangular  FIG. 389.	Rhombic  FIG. 390
$n > \text{Oil of Cloves}$	Isotropic	FLUORITE		
			Cryolite	CHABAZITE
$n > \text{Oil of Cloves}$ $n < \text{Bromoform}$	Isotropic	Alunite	APOPHYLLITE	
			ANHYDRITE	
$n > \text{Bromoform}$ $n < \alpha\text{-Monobrom-naphthalin}$	Isotropic			
			BARITE CELESTITE	BARITE CELESTITE

**D ACCORDING TO OPTICAL TESTS**

<b>Prismatic</b>  <b>Fig. 391.</b>	<b>Acicular</b>  <b>Fig. 392.</b>	<b>Platy (not previously included)</b>  <b>Fig. 393.</b>	<b>Irregular</b>  <b>Fig. 394.</b>
			<b>Allophane</b> <b>ANALCITE</b> <b>Lasurite</b> <b>LEUCITE</b> <b>OPAL</b> <b>Sodalite</b>
<b>STILBITE</b> <b>HEULANDITE</b> <b>Hydromagnesite</b> <b>GYPSUM</b> <b>Laumontite</b> <b>NATROLITE</b>	<b>Ulexite</b> <b>GYPSUM</b> <b>NATROLITE</b>	<b>HEULANDITE</b> <b>ORTHOCLASE</b> <b>MICROCLINE</b> <b>ALBITE</b> <b>GYPSUM</b>	<b>LEUCITE</b> <b>Cryolite</b> <b>Sepiolite</b> <b>CHALCEDONY</b>
		<b>Brucite</b>	
<b>NEPHELITE</b> <b>Wavellite</b> <b>WERNERITE</b>         <b>ARAGONITE</b>	<b>Brucite</b> <b>SERPENTINE</b> <b>Wavellite</b>	<b>CHLORITE</b> <b>PHLOGOPITE</b> <b>TALC</b> <b>LEPIDOLITE</b> <b>OLIGOCLASE</b> <b>LABRADORITE</b> <b>Amblygonite</b>	<b>CHRYSOCOLLA</b> <b>CHLORITE</b> <b>Garnierite</b> <b>NEPHELITE</b> <b>CHALCEDONY</b> <b>BERYL</b> <b>Iolite</b> <b>SERPENTINE</b> <b>QUARTZ</b> <b>Alunite</b>
		<b>BIOTITE</b>	
<b>WOLLASTONITE</b> <b>Glaucophane</b> <b>Pyrophyllite</b> <b>CALAMINE</b> <b>TOURMALINE</b> <b>TREMOLITE</b> <b>PREHNITE</b> <b>Vivianite</b> <b>ANDALUSITE</b> <b>ACTINOLITE</b>	<b>WOLLASTONITE</b> <b>TREMOLITE</b> <b>Pectolite</b> <b>ACTINOLITE</b>	<b>MUSCOVITE</b> <b>Margarite</b> <b>TOPAZ</b> <b>CALAMINE</b> <b>COLEMANITE</b>	<b>APATITE</b> <b>Turquois</b> <b>BARITE</b> <b>CELESTITE</b> <b>TOPAZ</b> <b>ANDALUSITE</b> <b>TOURMALINE</b> <b>Chondrodite</b> <b>PREHNITE</b> <b>DATOLITE</b>

1. The first part of the paper discusses the importance of understanding the underlying mechanisms of the observed phenomena. It highlights the need for a comprehensive theoretical framework that can account for the complex interactions between various factors. The authors argue that a purely descriptive approach is insufficient and that a more mechanistic understanding is required to make meaningful predictions and interventions.

2. The second part of the paper presents a detailed analysis of the data collected from the study. It includes a series of tables and figures that illustrate the patterns and trends observed. The authors carefully interpret these results, linking them back to the theoretical framework discussed in the first part. They identify key findings that support their hypotheses and also note areas where the data deviates from expectations.

3. The third part of the paper discusses the implications of the findings for future research and practice. The authors suggest several directions for further investigation, including the need for larger-scale studies and the exploration of additional variables. They also provide practical recommendations based on their findings, emphasizing the importance of a holistic and mechanistic approach in addressing the problem at hand.

4. The fourth part of the paper concludes the study by summarizing the main findings and reiterating the authors' conclusions. They emphasize the significance of the results and the potential impact of their work on the field. The authors also acknowledge the limitations of the study and express their appreciation for the support and assistance provided throughout the research process.

5. The final part of the paper is a brief discussion of the broader context of the research. It situates the study within the larger body of knowledge on the topic and highlights its contribution to the field. The authors express their hope that their work will inspire further research and lead to a deeper understanding of the phenomena under investigation.

6. The paper ends with a list of references, citing the works of other researchers in the field. This section provides a comprehensive overview of the literature that informed the study and allows readers to explore the topic further. The references are carefully selected to represent the most relevant and influential work in the area.

7. The paper is accompanied by a series of appendices that provide additional information and data. These include detailed descriptions of the study methods, raw data, and supplementary analyses. The appendices are designed to be self-contained and provide a complete picture of the research process and findings.

**Table 5.—Continued**  
**Minerals Arranged According to Optical Tests**

TABLE 5.—Continued. MINERALS

		Triangular	Rectangular	Rhombic
	Isotropic			
<p>n &gt; α-Monobrom-naphthalin n &lt; Methylene Iodid</p>			<p>Diopside (due to parting)</p>	<p>CALCITE DOLOMITE Ankerite MAGNESITE</p>
	Isotropic	SPHALERITE Diamond	Alabandite	
<p>n &gt; Methylene Iodid</p>				<p>RHODOCHRO SIDERITE SMITHSONITE</p>

# ARRANGED ACCORDING TO OPTICAL TESTS

	Prismatic	Acicular	Platy (not previously included)	Irregular
				Boracite SPINEL Stibiconite
	Zoisite ENSTATITE Hypersthene RHODONITE CYANITE Sillimanite HORNBLLENDE AUGITE DIOPSIDE Spodumene Diaspore Erythrite Strontianite Witherite Hübnerite	CYANITE Sillimanite	Diaspore	Triphylite VESUVIANITE Axinite STAUROLITE WILLEMITE OLIVINE Allanite
				CUPRITE GARNET HEMATITE LIMONITE SPHALERITE SPINEL
SITE	Zincite Atacamite Brochantite EPIDOTE Aegirite LIMONITE Gothite  Crocoite CERUSSITE			Pyromorphite CORUNDUM Chrysoberyl Zincite Scheelite Mimetite ANGLESITE Realgar EPIDOTE Monazite ZIRCON Vanadinite CASSITERITE CERUSSITE CINNABAR Proustite Pyrargyrite SULFUR Wulfenite AZURITE TITANITE RUTILE



the 1990s, the number of people in the world who are illiterate has increased from 1.2 billion to 1.5 billion. The number of illiterate people in the world is projected to reach 1.7 billion by the year 2015. The number of illiterate people in the world is projected to reach 1.7 billion by the year 2015. The number of illiterate people in the world is projected to reach 1.7 billion by the year 2015.

[illegible][illegible]

**TABLE 6**  
**Minerals Arranged According to Blowpipe and Chemical Tests.**

---

**Division 1—Carbonates.**

The mineral effervesces with

a common impurity in other

2. Some solids, *e.g.*, sphal.

H<sub>2</sub>S recognized by its odor.

---

The mineral is heated in the  
closed tube.

---

(a.) Turns dark on heating in

---

(b.) Turns yellow on heating  
tube.

---

(c.) No decided color change on

---

**Division 2—Sulfates.**

A water solution of the soda  
HCl. Note 1. It is always in  
the excess of Na<sub>2</sub>CO<sub>3</sub> always gi  
is taken.

---

(a.) Soluble in water (decided to

---

# ING TO BLOWPIPE AND CHEMICAL TESTS

## ON-METALIC LUSTER

### Fusibility

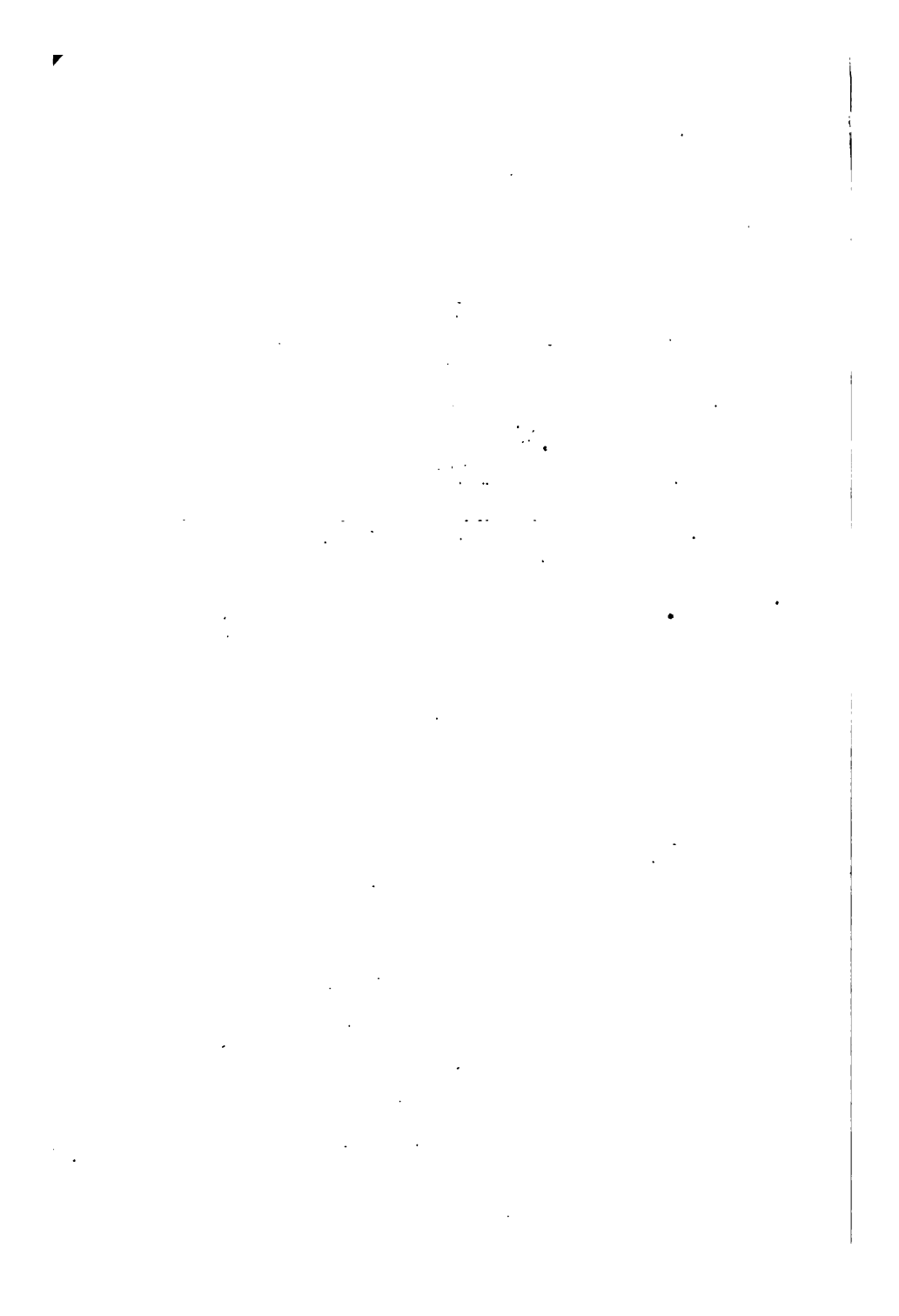
(b.) Soluble in HCl.	3½	GYPSUM	Ca	x
	3½	ANHYDRITE	Ca	
	3½	Brochantite	Cu	x
	7	Alunite	KAl	x
(c.) Insoluble in HCl. (Anhydrite is soluble with difficulty.)	4	BARITE	Ba	
	4	CELESTITE	Sr	
	2½	ANGLESITE	Pb	
	3½	ANHYDRITE	Ca	

### Division 3—Silicates.

Insoluble in  $\text{NaPO}_4$  bead. Confirm by dissolving soda fusion in dilute  $\text{HNO}_3$ . On evaporating the solution, gelatinous silica separates. The silica is dehydrated by carefully heating to dryness. Dilute HCl is added. Silica is filtered off. The metals are in the filtrate and may be tested for by the scheme on page—.

The finely powdered mineral is heated in HCl for several minutes. The solution is filtered off and evaporated on a watch-glass.

(a.) Gelatinizes with HCl.	2	DATOLITE	CaB	x
	2½	NATROLITE	NaAl	x
	2½	Laumontite	CaAl	x
	2½	Allanite	AlFeCaCe	x
	3½	Lasurite	NaAlS	
	4	Sodalite	NaAlCl	
	4	NEPHELITE	NaAl	
	5	WILLEMITE	ZnMn	
	6	CALAMINE	Zn	x
	7	OLIVINE	MgFe	
	7	Allophane	Al	x
	7	Chondrodite	MgF	
	7	WILLEMITE	Zn	
(b.) Decomposed by HCl without gelatinization.	2	APOPHYLLITE	KCa	x
	2	PREHNITE	CaAl	x
	2½	Pectolite	CaNa	x
	3	CHABAZITE	CaNaAl	x
	3	STILBITE	CaNaAl	x
	3	HEULANDITE	CaNaAl	x
	3	ANALCITE	NaAl	x
	3	WERNERITE	CaAlNaCl	
	4	WOLLASTONITE	Ca	
	4	TITANITE	CaTi	
	4½	LÄBRADORITE	CaAlNa	
	5	SERPENTINE	Mg,Fe	x
	5	Sepiolite	Mg	x
	7	CHRYSOCOLLA	Cu	x
	7	Garnierite	Ni,Mg	x
	7	LEUCITE	KAl	



**TABLE 6.—Continued**  
**Minerals Arranged According to Blowpipe and Chemical Tests**

TABLE 6.—Continued. MINERALS ARRANGED A

## A. MINERALS WITH NON-ME

## Division 3—Silicates—Continued

## Fusibility

c. Insoluble (or nearly so) in HCl.

\*Means soluble in HCl after fusion (alone, not with  $\text{Na}_2\text{CO}_3$ ).

2	LEPIDOLITE	LiKAl	x
2½	PREHNITE	CaAl	x
2½	Axinite	CaAlB	
3	*GARNET	AlFeCaMg	
3	Glaucophane	NaAlMgFe	
3	Aegirite	FeNa	
3	*VESUVIANITE	CaAl	x
3	WERNERITE	CaNaAlCl	
3½	RHODONITE	Mn	
3½	Spodumene	LiAl	
3½	TOURMALINE	MgAlB	
3½	*EPIDOTE	CaAlFe	x
3½	Zoisite	CaAl	x
4	TITANITE	CaTi	
4	TREMOLITE	CaMg	
4	ACTINOLITE	CaMgFe	
3½	HORNBLLENDE	AlCaMgFe	
4	DIOPSIDE	CaMgFe	
4	AUGITE	AlCaMgFe	
4½	ALBITE	NaAl	
4½	OLIGOCLASE	NaCaAl	
4½	LABRADORITE	CaNaAl	
4½	PHLOGOPITE	MgFeAlK	x
4½	Margarite	CaAl	x
5	MUSCOVITE	KAl	x
5	BIOTITE	FeKAl	x
5	ORTHOCLASE	KAl	
5	MICROCLINE	KAl	
5	Hypersthene	MgFe	
5	*TOURMALINE	FeAlB	
5½	TALC	Mg	x
5½	CHLORITE	AlMgFe	x
5½	BERYL	BeAl	
6	ENSTATITE	Mg	
7	CYANITE	Al	
7	Kaolinite	Al	x
7	QUARTZ		
7	CHALCEDONY		
7	OPAL		x
7	TOPAZ	AlF	
7	STAUROLITE	AlFeMg	x
7	ANDALUSITE	Al	
7	Sillimanite	Al	
7	PYROPHYLLITE	Al	
7	Zircon	Zr	

Infusible

§ ACCORDING TO BLOWPIPE AND CHEMICAL TESTS

METALLIC LUSTER.—Continued

Division 4—Phosphates and Arsenates.—The  $\text{HNO}_3$  solution of the soda fusion gives a yellow ppt. with  $(\text{NH}_4)_2\text{MoO}_4$  (with phosphates on gentle heating and with arsenates on boiling.)

Fusibility

	2½	Vivianite	FeP	x
	2½	Triphylite	FeLiMnP	x
	2½	Olivenite	CuAs	x
	7	Turquoise	AlCuP	x.
	7	Wavellite	AlP	x
	2	Amphibysomite	LiAlP	x
	2	Pyromorphite	PbPbCl	
	1½	Mimetite	PbAsCl	
	5½	APATITE	CaPbCl	
	2½	Erythrite	CoAs	x
	7	Monasite	CeLaDiP	

Division 5—Chromates, Vanadates, and Molybdates.

The  $\text{NaPO}_3$  bead in R. F. is bright green. (Note other colors for future use.)

a. The $\text{NaPO}_3$ bead in O. F. is green.	7 1½	CHROMITE <i>Garnetite</i>	FeCr PbCr	
b. The $\text{NaPO}_3$ bead in O. F. is yellow	1½	Vanadinite	PbClV	
c. The $\text{NaPO}_3$ bead in O. F. is colorless.	2	Wulfenite	PbMo	

Division 6.—Chlorids.

The  $\text{NaPO}_3$  bead saturated with  $\text{CuO}$  (or malachite) gives a blue flame when heated with the mineral.

a. Soluble in water (decided taste).	1½ 1½ 1½ 1½	HALITE Sylvite Sal ammoniac Carnallite	Na K $\text{NH}_4$ KMg	x
b. Insoluble in water.	1 2 3½	Cerarygyrite Atacamite Boracite	Ag Cu MgB	x



THE  
JOURNAL OF THE  
ROYAL ANTHROPOLOGICAL INSTITUTE  
VOLUME 10  
PART 1  
1980

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**TABLE 6.—Continued**  
**Minerals Arranged According to Blowpipe and Chemical Tests**

TABLE 6.—Continued. MINERALS ARRANGED

## A. MINERALS WITH NON-METALIC LUSTER—continued

## Division 7—Not previously included.

Mostly oxides and hydroxides, a few sulfides, borates, etc.

## Fusibility

(a) On charcoal R.F. gives a garlic odor (As)	1 1 1	Realgar Orpiment Proustite	AsS As <sub>2</sub> S AsAgS	
(b) On charcoal gives dense white fumes (Sb) and white coating	7	Stibiconite	Sb	X
(c) On charcoal R.F. gives magnetic residue (Fe)	5½ 5½ 5½	HEMATITE LIMONITE Goethite	Fe Fe Fe	x x
(d) On charcoal R.F. gives metallic globules but no magnetic residue	3 3 7	CUPRITE Melanconite CASSITERITE	Cu Cu Sn	
(e) Borax bead tests for Mn.	7 7 7 4 7	WAD PYROLUSITE PSILOMELANE Hübnerite Zinnite	Mn Mn Mn MnW ZnMn	x x
(f) Fusible minerals, not previously included	1 1 1 1½ 1½ 1½ 1½ 1½ 2 3 5 5	SULFUR Niter Soda Niter CINNABAR Borax Ulexite COLEMANITE Cryolite Boracite FLUORITE SPHALERITE Scheelite	S KCN NaN HgS NaB CaNaB CaB NaAlF MgClB CaF ZnS CaW	x x x x
(a) Infusible minerals, not previously included	7 7 7 7 7 7 7 7 7 7	CORUNDUM SPINEL Chrysoberyl BAUXITE Diaspore RUTILE CASSITERITE Bucite Diamond	Al MgAl BeAl Al Al Ti Sn Mg C	x x x

## Division 8—Sulfids and Sulfos

The soda fusion made on mica stains a moistened silver coin

(Sulfids from previous division: tite, sphalerite, and cinnabar.)

## Fusibility

(a) On charcoal R.F. gives a garlic odor (As)	2 2½ 1	
(b) On charcoal gives white coating near assay and dense white fumes (Sb)	1 1½ 1 1 1 1	
(c) On charcoal R.F. gives a magnetic residue	3 3 3 2 2½ 1½ 2 5	
(d) On charcoal R.F. gives metallic globules, but no magnetic residue	2 1½ 2½ 2½ 1 1 1	
(e) Borax bead test for Mn.	3	
(f, g) Not previously included	7	

▲

Non-salts.  
minerals (or platinum foil) with O.F.  
reagent.

are realgar, orpiment, prou-

stite.

By

ARSENOPYRITE  
*Cobaltite*  
Enargite

FeAs  
CoAs  
CuAs

STIBNITE  
TETRAHEDRITE  
*Bournonite*  
*Jamesonite*  
Pyrargyrite  
Stephanite  
Polybasite

Sb  
CuSb  
CuPbSb  
PbSb  
AgSb  
AgSb  
AgCuSb

PYRITE  
MARCASITE  
PYRRHOTITE  
CHALCOPYRITE  
BORNITE  
*Stannite*  
*Millerite*  
SPHALERITE

Fe  
Fe  
Fe  
CuFe  
CuFe  
CuSnFe  
Ni  
ZnFe

GALENA  
*Argentite*  
CHALCOCITE  
Covellite  
Bismuthinite  
Calaverite  
*Sylvanite*

Pb  
Ag  
Cu  
Cu  
Bi  
AuTe  
AgAuTe

Alabandite

Mn

Molybdenite

Mo

Division 9—Not previously included.  
Mostly oxides hydroxides, and metals.

Fusibility

(a) On charcoal R.F. gives  
garlic odor (As).

1  
2½  
2

Arsenic  
Smailite  
Nissolite  
Löllingite

As  
CoNiAs  
NiAs  
FeAs

(b) On charcoal gives dense  
white fumes.

1

Antimony

Sb

(c) On charcoal R.F. gives  
magnetic residue.

5½  
5½  
5½  
7  
7  
7  
4  
2½

HEMATITE  
LIMONITE  
MAGNETITE  
Iron  
ILMENITE  
Franklinite  
Wolframite  
Allanite

Fe  
Fe  
Fe  
Fe  
FeTi  
FeMnZn  
FeMnW  
AlFeCaCe

(d) On charcoal R.F. gives  
metallic globules, but no  
magnetic residue.

1  
2  
3  
3  
7

Bismuth  
SILVER  
COPPER  
CUPRITE  
~~Melnicomite~~  
CASSITERITE

Bi  
Ag  
Cu  
Cu  
Cu  
Sn

(e) Borax bead tests for  
Mn.

7  
7  
7

PYROLUSITE  
MANGANITE  
PSILOMELANE

Mn  
Mn  
Mn

(f) Fusible minerals not  
previously included.

5½

Columbite

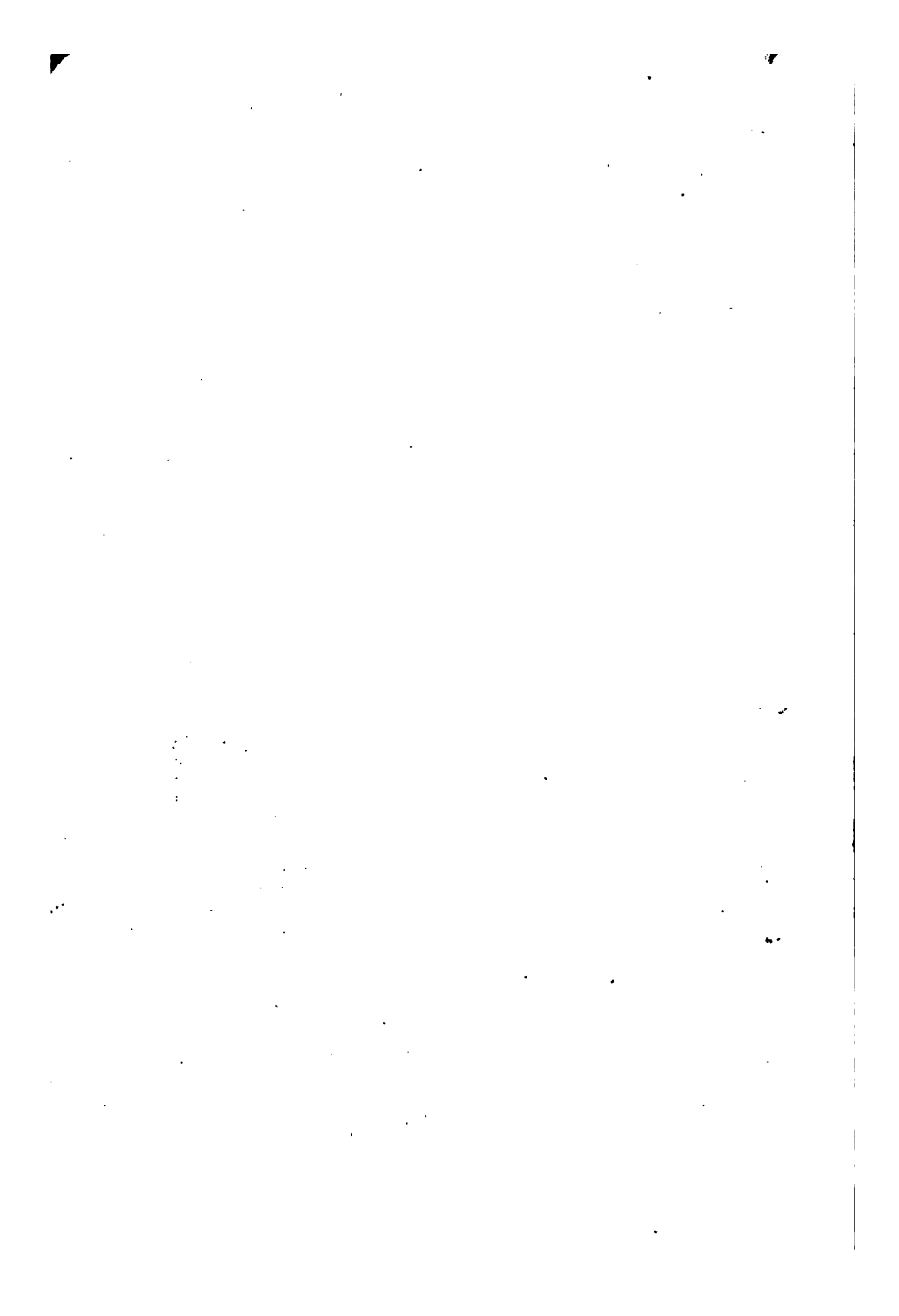
FeMnNb

(g) Infusible minerals not  
previously included.

7  
7  
7  
7

GRAPHITE  
RUTILE  
CASSITERITE  
Uraninite  
Platinum

C  
Ti  
Sn  
U  
Pt



# PART VI

## THE DESCRIPTION OF IMPORTANT MINERALS

### Introductory

The modern classification of minerals is primarily a chemical one, the minerals being arranged according to the acid radical, and secondarily a crystallographic one, for in any chemical division minerals of similar chemical composition, which are related crystallographically, are placed together in a group. Thus, the sulfates barite, ( $\text{BaSO}_4$ ); celestite, ( $\text{SrSO}_4$ ); and anglesite, ( $\text{PbSO}_4$ ), constitute the barite group, as they all crystallize in the orthorhombic system, and though the habit may vary, the angles between corresponding faces are almost identical. The facts stated in discussing isomorphism and isomorphous mixtures (see page 173) are the principles used in classifying minerals. This is the so-called **systematic classification** and is regarded as the most scientific one.

Minerals are sometimes arranged according to a metallic classification, except for the silicates. Though there may be some advantages in this method, it separates many very similar minerals and unites many unlike ones. It is also inconsistent in that silicates are classified on a different basis from the other minerals.

All mineral specimens which have essentially the same chemical composition and the same crystal form constitute a **mineral species**. Those specimens of any mineral species which have the same peculiarity of color, impurity, crystal habit, or mode of aggregation constitute a **variety**. These varietal distinctions are

based upon non-essential properties, and the present tendency in mineralogy is to use varietal names (~~in this sense~~) as little as possible. Varieties should be based upon occurrence, association, and origin (see numbered list under the heading *Occurrence* of each mineral).

About a thousand distinct kinds of minerals or mineral species are known. Most of these are very rare, many of them being found at only one or two localities. In this book two hundred minerals are considered. These include all the common minerals, most of those of economic importance, and others which are intended to give the student a comprehensive view of the mineral kingdom as a whole.

The derivation of mineral names deserves a little space at this point. The following names are in honor of prominent scientific men: biotite (Biot, French physicist), brucite (Bruce, an early American mineralogist), dolomite (Dolomieu, French geologist), göthite (Goethe, the German poet), millerite (Miller, English crystallographer), scheelite (Scheele, Swedish chemist), smithsonite (Smithson, founder of the Smithsonian Institution), wollastonite (Wollaston, English chemist).

The following are geographical names based upon prominent localities: andalusite (Andalusia, a province of Spain), aragonite (Aragon, ancient kingdom in Spain), anglesite (Anglesea in Wales), bauxite (Beaux in France), copiapite (Copiapo in Chile), ilmenite (Ilmen mountains in the Urals), labradorite (Labrador), muscovite (Moscow in Russia), strontianite (Strontian in Scotland), vesuvianite (Mt. Vesuvius in Italy).

The following are derived from the Latin or Greek names for colors: albite (white), azurite (blue), crocoite (saffron), cyanite (blue), celestite (sky-blue), chlorite (green), erythrite (red), hematite (blood), leucite (white), rhodonite (rose-red), rutile (reddish).

As will be recognized, the following names are based upon the chemical composition: alunite, argentite, arsenopyrite, barite, calcite, chromite, cobaltite, cuprite, hydrozincite, magnesite,

molybdenite, natrolite, siderite, sodalite, stannite, stibnite, titanite, uraninite, wolframite, zincite.

It will be noticed that most mineral names end in *-ite* (the suffix *-ites* or *-itiš'*, signifying a quality, use, or locality of the mineral). Names in use before this custom was adopted are quartz, opal, topaz, garnet, mica, diamond, galena, beryl, zircon, gypsum, and hornblende.

It is interesting to note that at one time a binomial nomenclature like that at present used for plants and animals was employed for minerals. Thus, barite was known as *Baralus ponderosus* and celestite as *Baralus prismaticus*.

The order followed in the description of the important minerals is practically that of Dana's *System of Mineralogy* (6th edition) except that silicates are placed last.



## **SYNOPSIS OF THE CLASSIFICATION OF MINERALS**

- 1. ELEMENTS**
- 2. SULFIDS, ARSENIDS, AND  
TELLURIDS**
- 3. SULFO-SALTS**
- 4. HALOIDS**
- 5. OXIDS**
- 6. ALUMINATES, FERRITES, ETC.**
- 7. HYDROXIDS**
- 8. CARBONATES**
- 9. PHOSPHATES, ARSENATES, ETC.**
- 10. NITRATES AND BORATES**
- 11. SULFATES**
- 12. TUNGSTATES AND MOLYBDATES**
- 13. SILICATES**

## 1. ELEMENTS

### A. Non-metals

Diamond	C
GRAPHITE	C
SULFUR	S

### B. Semi-metals

{ Arsenic	As
{ Antimony	Sb
{ Bismuth	Bi

### C. Metals

GOLD	Au
SILVER	Ag
COPPER	Cu
Mercury	Hg
Platinum	Pt
Iron	Fe

### Diamond, C

**Form.** Diamond is nearly always found in small loose crystals with rounded faces and curved edges. It crystallizes in the isometric system, probably in the hextetrahedral class. Though many of the isometric forms have been observed the only common one is the octahedron. Fig. 395 represents a typical crystal with grooved edges and triangular markings. Spinel twins of diamond are rather common.

**Cleavage.** Perfect octahedral. This fact enables the diamond-cutter to save considerable work.

**H.** = 10 (the hardest known substance).

**Sp. gr.**  $\pm 3.5$

**Color.** Diamond is usually colorless or pale yellow, though

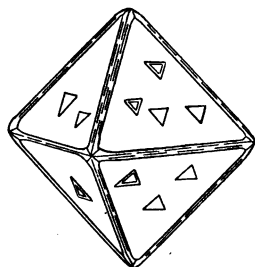


FIG. 395.—Diamond crystal.

brilliantly colored blue, green, and red stones are known. One variety known as carbonado is black and opaque.

**Luster.** The luster is the brilliant luster known as adamantine.

**Optical Properties.** The index of refraction is very high ( $n=2.42$ ) which accounts for its brilliancy. The "fire" of the diamond is accounted for by its strong dispersion, the index of refraction for the red end of the spectrum being 2.402, while for the violet end it is 2.465. Diamonds are transparent to X-rays, while imitations are opaque.

**Chemical Composition.** Pure carbon. Upon heating the diamond in an atmosphere of oxygen it is converted into  $\text{CO}_2$ . On heating out of contact with air it is converted into graphite.

**Blowpipe Tests.** Infusible. Insoluble in acids.

**Uses.** On account of its great hardness, brilliancy, and rarity, diamond stands as the gem mineral, *par excellence*. Among the famous historic diamonds are the Kohinoor, 186 carats; the Regent, 137 carats; the Star of the South, 254 carats; the Imperial, 457 carats; and the Excelsior, 969 carats. Of colored diamonds the most famous are the Tiffany (yellow), the Hope (blue), and the Dresden (green). The largest diamond on record is the Cullinan, found in 1905 at the Premier mine in the Transvaal. This diamond weighed 3025 carats (621.2 grams or about 1.37 pounds avoirdupois).

Diamonds are also used as an abrasive in cutting and polishing precious stones, glass, and other materials. The center of the diamond cutting industry is Amsterdam.

Several mines within an area of ten square miles at Kimberley, South Africa, have furnished the world's principal supply of diamonds since their discovery in 1867.

A black opaque non-cleavable variety of diamond is used for diamond drills. It is found only in Bahia, Brazil, and is known as *carbonado* or "black diamond."

**Occurrence.** 1. In volcanic necks and dikes of a rock known as kimberlite (locally called "blue-ground"). Kimberlite is an

altered peridotite composed of fragments of pyrope, pyroxene, biotite, olivine, etc., in a matrix of serpentine. The origin of the diamond is in doubt, but many believe it to be of igneous origin.

Diamonds have recently been found in peridotite dikes in Pike County, Arkansas.

2. In alluvial deposits associated with heavy minerals. Among these localities may be mentioned southern India, (where diamonds were first found), the states of Bahia and Minas Geraes, Brazil (one locality is known as Diamantina), and scattered localities throughout the United States. In the Great Lakes region diamonds are found in glacial drift. In California small diamonds have frequently been found in sluice-boxes along with gold.

3. In meteorites from Canon Diablo (Arizona) minute diamonds have been found. Moissanite,  $\text{SiC}$ , the same as the artificial carborundum, is also found there. A peridotite meteorite which fell at Novo-Urei, Russia in 1886 also contained diamonds. Moissan obtained small diamonds by cooling in water a block of soft iron saturated with carbon.

### GRAPHITE, C

**Form.** Graphite occurs occasionally in six-sided tabular crystals, but more often in foliated masses, minute disseminated scales, or earthy lumps.

**Cleavage.** Cleavage in one direction.

**H** = 1–2.

**Sp. gr.**  $\pm 2.1$

**Color.** Dark gray to black. Luster, metallic. Streak, gray. Opaque. Sectile.

**Chemical Composition.** Graphite is a modification of carbon. It grades from pure carbon to earthy varieties which yield a large amount of ash on combustion.

**Blowpipe Tests.** Infusible. Insoluble in acids. With  $\text{KClO}_3$  and conc.  $\text{HNO}_3$ , graphite is converted into a yellow transparent scaly substance called graphitic acid. This distinguishes graphite from amorphous carbon.

**Uses.** Graphite is used in the manufacture of lead pencils (varying hardness is due to admixed clay), lubricants for machinery, refractory crucibles, and electrical supplies. Austria and Ceylon are the chief producers.

Artificial graphite is now made from anthracite in the electric furnace at Niagara Falls.

**Occurrence.** 1. In crystalline limestones. Franklin, New Jersey.

2. In schists and gneisses often as an essential constituent.

3. In true fissure-veins (Ceylon).

4. In meteorites. Paramorphs of graphite after diamond, called cliftonite, are also found in meteorites.

## SULFUR, S

**Form.** Sulfur occurs in crystals, incrustations, disseminations, and compact masses. The crystals are good examples of the orthorhombic system. Usual forms:  $p\{111\}$ ,  $c\{001\}$ ,  $n\{011\}$ ,

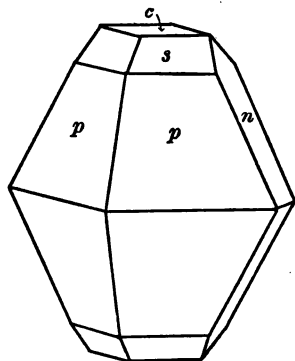


FIG. 396.

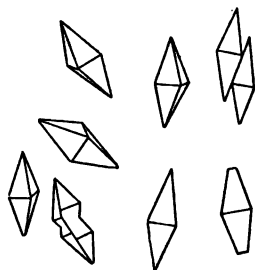


FIG. 397.

and  $s\{113\}$ . The habit is usually pyramidal, being determined by  $\{111\}$ . Interfacial angles:  $pp(111:1\bar{1}1)=94^\circ 52'$ ,  $cp(001:111)=71^\circ 40'$ ,  $cs(001:113)=45^\circ 10'$ ,  $pn(001:011)=62^\circ 17'$ . Fig. 396 is the common type of crystal and Fig. 397

shows the crystals formed by the evaporation of a carbon bisulfid solution.

**H.** = 2.

**Sp. gr.**  $\pm 2.0$

**Color.** Yellow, sometimes with orange, brown, or green tinge.

**Optical Properties.**  $n_r(2.24) - n_a(1.95) = 0.29$ . Fragments are irregular with high-order interference colors.

**Chemical Composition.** Sulfur, often with such impurities as clay and asphaltum.

**Blowpipe Tests.** Fuses easily ( $114^\circ \text{C.}$ ) and burns with a blue flame, giving off sulfur dioxide.

Insoluble in acids. Soluble in carbon bisulfid and in methylene iodid.

**Uses.** Sulfur is used in the manufacture of gunpowder, matches, for vulcanizing rubber, and for the production of sulfur dioxide, which is used in paper manufacturing and bleaching. It was formerly used in the manufacture of sulfuric acid, but that is now made from pyrite. The island of Sicily and southwestern Louisiana are the principal sources of sulfur. At the latter locality the sulfur is obtained by dissolving it in superheated steam and pumping the solution to the surface.

**Occurrence.** 1. As a sublimate in the crevices around volcanoes (called solfataras). Formed by the incomplete oxidation of hydrogen sulfid.  $2\text{H}_2\text{S} + \text{O}_2 = 2\text{S} + 2\text{H}_2\text{O}$ .

2. In sedimentary rocks formed by the decomposition of such sulfates as gypsum. At Girgenti, Sicily, sulfur occurs in marl associated with gypsum, celestite, and aragonite.

3. As a decomposition product of sulfids such as galena, sphalerite, and pyrite.

4. Formed by some bacteria in sulfate bearing waters.

### ARSENIC GROUP—HEXAGONAL

The three semi-metals or metalloids, arsenic, antimony, and bismuth are isomorphous, for they crystallize in the scalenohedral class of the hexagonal system and have rhombohedral cleavage

with angles of about  $92^{\circ}$ – $94^{\circ}$  and parting parallel to  $\{01\bar{1}2\}$  (like calcite). Crystals are very rare.

### Arsenic, As

**Form.** Arsenic usually occurs in mammillary crusts made up of concentric layers or in granular masses, rarely in small imperfect crystals.

**Cleavage** may be noticed in coarse-grained specimens.

**H** =  $3\frac{1}{2}$ .

**Sp. gr.**  $\pm 5.7$

**Color.** Tin white, tarnishing black on exposure. Luster, metallic.

**Chemical Composition.** Arsenic, usually with a little antimony.

**Blowpipe Tests.** On charcoal easily volatile with the characteristic arsin odor, giving a white sublimate some distance from the assay.

Oxidized by  $\text{HNO}_3$  to arsenic acid.

**Occurrence.** 1. As a vein mineral often associated with silver and cobalt minerals. Schneeberg, Saxony, is a prominent locality.

### Antimony, Sb

**Form.** Antimony occurs in massive lamellar or granular crystalline aggregates, occasionally cleavable, but rarely crystallized.

**Cleavage** often prominent.

**H.** =  $3\frac{1}{2}$ .

**Sp. gr.**  $\pm 6.6$

**Color.** Tin-white (does not tarnish easily like arsenic).

**Chemical Composition.** Antimony, usually with some arsenic.

**Blowpipe Tests.** On charcoal easily volatile, giving dense white fumes (without odor) and a white sublimate near the assay.

Oxidized by  $\text{HNO}_3$  to  $\text{HSbO}_3$ , a white residue.

**Occurrence.** 1. As a vein mineral often associated with stibnite and with silver minerals.

**Bismuth, Bi**

**Form.** Bismuth occurs in small cleavable masses or in embedded dendritic forms.

**Cleavage** often prominent.

**H.** =  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 9.8$

**Color.** Pale reddish tin-white. Luster, metallic.

**Chemical Composition.** Bismuth.

**Blowpipe Tests.** Easily fusible (1) to a malleable globule which is brittle on the edges. With bismuth flux on charcoal gives a bright red sublimate.

Soluble in  $\text{HNO}_3$ . The solution diluted with water gives a white precipitate,  $(\text{BiO})\text{NO}_3$ .

**Uses.** Native bismuth is the chief source of the bismuth of commerce which is used principally in alloys.

**Occurrence.** 1. As a vein mineral, usually associated with silver and cobalt minerals. Schneeberg, Saxony, is the principal locality.

**GOLD, Au**

**Form.** Though usually finely disseminated through rock and only apparent on assaying, gold also occurs in rolled grains and scales, occasionally in large nuggets, also in crystals and imperfect crystal aggregates. Like many of the metals, gold crystallizes in the isometric system, the octahedron being the only common form. Sheets of gold (leaf-gold) with raised triangular markings are not uncommon.

**H.** =  $2\frac{1}{2}$  to 3.

**Sp. gr.** 15 to 19 (according to fineness).

**Color.** Deep to pale yellow. The pale yellow varieties contain silver. Luster, metallic. Very malleable.

**Chemical Composition.** Gold, usually alloyed with more or less silver, sometimes also with Bi, Cu, Fe, Pd, and Rh. The following analyses give an idea of the variation in the chemical composition:



## Analyses of Gold

	Au	Ag	Misc.	Sp. Gr.
South Australia, . . . . .	93.5	6.5	.....	18.8
Urals, . . . . .	87.4	12.1	Cu = 0.1	17.4
Peru, . . . . .	79.9	20.1	.....	16.6
Verespatak, . . . . .	66.4	33.2	SiO <sub>2</sub> = 0.4	15.0

Gold with more than 20 per cent. of silver is called *electrum* and is very pale yellow in color.

**Blowpipe Tests.** Fusible at 3. With mercury forms an amalgam.

Soluble in aqua regia, the silver bearing varieties leaving a residue of AgCl.

**Uses.** The uses of gold are well-known.

**Occurrence.** 1. In quartz veins along with pyrite, chalcopryrite, sphalerite, arsenopyrite, etc.

2. In placers along streams (ancient river-channels in some cases) associated with heavy minerals such as magnetite, ilmenite, garnet, zircon, platinum, etc. Prominent localities are Alaska, California, Brazil, Colombia, Urals, and Australia.

3. In quartzite-conglomerate in the Rand, Transvaal, South Africa. The origin of the gold is in doubt.

4. As a secondary mineral in gossan. At Cripple Creek, gold is found in the oxidized zone pseudomorphous after calaverite.

## SILVER, Ag

**Form.** The characteristic occurrence of silver is in wires, thin sheets, skeleton crystals, dendritic groups, and masses. The cube is the only common crystal form, but the crystals are very small.

H. = 2½.

Sp. gr. ± 10.5

**Color.** Tin-white to pale yellow, but is often tarnished sometimes resembling copper. Luster, metallic. Malleable.

**Chemical Composition.** Silver, often with some gold and copper.

**Blowpipe Tests.** Easily fusible (2) to a malleable button.

Soluble in  $\text{HNO}_3$ .  $\text{HCl}$  gives a white precipitate ( $\text{AgCl}$ ), which turns violet on standing and is soluble in  $\text{NH}_4\text{OH}$ .

**Uses.** Native silver is the source of some silver. The Cobalt (Ontario) district now furnishes about one-fifth of the world's supply of silver, the silver being mostly in the form of the native metal.

**Occurrence.** 1. In veins along with bismuth, cobalt minerals, and other silver minerals. Batopilas, Mexico, and Cobalt, Ontario, are prominent localities.

2. As a secondary mineral with argentite or galena or in the gossan and formed from other silver minerals. Leadville, Colorado, and the Coeur d'Alene district in Idaho are prominent localities.

In contrast with gold, silver is never found in placers.

## COPPER, Cu

**Form.** Copper is found in small disseminated grains, in sheets, and occasionally in large masses. Copper crystallizes in the isometric system, but the crystals are usually distorted and made up of dendritic groups. The forms {100}, {111}, {110}, and {210} can sometimes be made out.

**H.** =  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 8.8$

**Color.** Copper-red, often tarnished and also incrustated with alteration products such as cuprite and malachite. Metallic luster.

**Chemical Composition.** Copper, often with a little silver.

**Blowpipe Tests.** Fusible (3) to a malleable globule.

Soluble in dilute  $\text{HNO}_3$  to a green solution with the evolution of  $\text{NO}_2$ . Also soluble in  $\text{NH}_4\text{OH}$ , giving a deep blue solution.

**Uses.** Native copper is an important source of copper in but one locality (Upper Peninsula of Michigan).

**Occurrence.** 1. As a secondary mineral in many copper mines formed by the reduction of copper compounds in solution, which in turn were formed by the oxidation of chalcopyrite.

2. In amygdaloidal cavities of diabase associated with calcite, datolite, prehnite, epidote, zeolites, and sometimes with silver. The Upper Peninsula of Michigan is the type locality.

### Mercury, Hg

**Form.** Mercury occurs as small globules in seams and cavities associated with cinnabar, occasionally in little pools. Mercury is unique in being the only mineral which is liquid at ordinary temperatures.

**Color,** Tin-white.

**Sp. gr.**  $\pm 13.6$

**Chemical Composition.** Mercury.

**Blowpipe Tests.** Volatile. Forms an amalgam with gold, silver, and copper.

Soluble in  $\text{HNO}_3$ .

**Occurrence.** 1. Probably a secondary mineral formed by the decomposition of cinnabar. Found at New Almaden, California.

### Platinum, Pt

**Form.** Platinum is found in rounded grains, scales, and irregular lumps. Cubic crystals are very rare.

**H.**  $= 4\frac{1}{2}$ .

**Sp. gr.** 15-19 (21, if pure)

**Color.** Light steel gray. Luster, metallic. Malleable. Some varieties are magnetic.

**Chemical Composition.** Platinum, often alloyed with iron and metals of the platinum group (Ir, Os, Pd, Rh). Analyses:

	Pt	Fe	Pd	Rh	Ir	Os	Cu	
Urals .....	80.9	2.3	1.6	11.1	tr	.....	1.0	S=0.8
Colombia .....	84.8	8.3	1.0	2.1	1.0	1.0	0.6	
California .....	79.8	9.4	0.3	3.4	4.3	1.1	0.3	

**Blowpipe Tests.** Infusible.

Soluble in aqua regia. From this solution KCl precipitates  $K_2PtCl_6$ , a yellow crystalline powder composed of minute octahedra.

**Uses.** Native platinum is the only source of platinum. The Ural mountains furnish the main supply.

**Occurrence.** 1. In placer deposits along with gold, magnetite, ilmenite, zircon, diamond, etc. Prominent localities are the Ural Mts., Colombia, British Columbia, northern California, and southern Oregon.

2. In peridotites with chromite, olivine, and serpentine. These rocks are the original source of the platinum of placers. Urals and British Columbia.

**Iron, Fe**

**Form.** Iron is found in compact or spongiform masses and in disseminated grains. Iron crystallizes in the isometric system, but distinct crystals are exceedingly rare. Many meteoric irons have an octahedral structure which is revealed by etching with  $HNO_3$ .

**H.** =  $4\frac{1}{2}$ .

**Sp. gr.**  $\pm 7.5$

**Color.** Steel-gray to iron-black, often covered with iron-rust. Luster, metallic. Attracted by the magnet.

**Chemical Composition.** Iron, often alloyed with nickel. Contains small amounts of Co, Cu, C, etc.

	Fe	Ni	Co	Cu	S	Mn	C	Silicates, Insol.
Terrestrial iron, Greenland.	91.7	1.7	0.5	0.1	0.1	....	1.4	3.9
Meteoric iron, Siberia.	88.0	10.7	0.5	0.1	tr.	0.1	0.1	0.5

**Blowpipe Tests.** Infusible. Amber borax bead in O.F., bottle green in R.F.

Soluble in HCl with the evolution of hydrogen. Iron is copper-coated by a solution of copper sulfate.

**Occurrence.** 1. In meteorites, either as the main constituent or associated with silicates such as olivine.

2. In basalts, perhaps formed from the molten magma. The only prominent locality is Disco Island, Greenland.

## 2. SULFIDS, ARSENIDS, AND TELLURIDS

Realgar,	AsS
Orpiment,	As <sub>2</sub> S <sub>3</sub>
{ STIBNITE,	Sb <sub>2</sub> S <sub>3</sub>
{ Bismuthinite,	Bi <sub>2</sub> S <sub>3</sub>
Molybdenite,	MoS <sub>2</sub>
{ Argentite,	Ag <sub>2</sub> S
{ GALENA,	PbS
CHALCOCITE,	Cu <sub>2</sub> S
SPHALERITE,	ZnS
Alabandite,	MnS
CINNABAR,	HgS
Covellite,	CuS
Millerite,	NiS
Niccolite,	NiAs
PYRRHOTITE,	FeS
{ PYRITE,	FeS <sub>2</sub>
{ Cobaltite,	CoAsS
{ Smaltite,	(Co,Ni)As <sub>2</sub>
{ MARCASITE,	FeS <sub>2</sub>
{ ARSENOPYRITE,	FeAsS
Löllingite,	FeAs <sub>2</sub>
Sylvanite,	AgAuTe <sub>4</sub>
Calaverite,	AuTe <sub>2</sub>

The sulfids and their analogues, the selenids, tellurids, arsenids, etc., are derivatives of H<sub>2</sub>S, H<sub>2</sub>Se, H<sub>2</sub>Te, H<sub>2</sub>As, etc. They may be considered as salts of these acids or as sulfanhydrids of sulfo-salts just as the oxids are anhydrids of the oxy-salts. They are mostly sulfids of the heavy metals. The sulfids may be divided into two classes: (1) the sulfids of the semi-metals, and (2) the sulfids of the metals. Minerals under each of these are arranged according to increasing number of sulfur atoms in the formula. Prominent isomorphous groups are indicated by brackets.

**Realgar, AsS**

**Form.** Realgar occurs incrusting or disseminated, and is usually massive, rarely showing distinct crystals. Crystals are monoclinic and short prismatic in habit.

**H.** =  $1\frac{1}{2}$  – 2.

**Sp. gr.**  $\pm 3.5$

**Color.** Red, becoming orange-red on exposure to light. Luster, resinous. Translucent.

**Optical Properties.**  $n > 1.93$ . Double refraction strong. Fragments are irregular and pleochroic (yellow to orange).

**Chemical Composition.** Arsenic sulfid, AsS; (As = 70.1 per cent.).

**Blowpipe Tests.** On charcoal fuses (at 1) and volatilizes, giving off fumes of arsin and sulfur dioxide. In the closed tube gives a red sublimate (AsS).

Soluble in KOH.

**Occurrence.** 1. As a vein mineral often associated with orpiment. At Felsöbanya, Hungary, realgar occurs in veins with barite, arsenic, orpiment, stibnite, quartz, pyrite, etc.

2. As a sublimation product in solfataras, and in the workings or dumps of burning coal mines.

**Orpiment, As<sub>2</sub>S<sub>3</sub>**

**Form.** Orpiment occurs in foliated or granular masses, in powdery incrustations, and in small indistinct orthorhombic crystals.

**Cleavage.** Perfect cleavage in one direction (010).

**H.** =  $1\frac{1}{2}$ .

**Sp. gr.**  $\pm 3.5$

**Color.** Yellow. Cleavage plates are flexible and have a pearly luster.

**Optical Properties.**  $n > 1.93$ . Double refraction, strong. Cleavages have extinction parallel to striations, but give no interference figure.

**Chemical Composition.** Arsenic sulfid, As<sub>2</sub>S<sub>3</sub>; (As = 60.9 per cent.).

**Blowpipe Tests.** Like those of realgar except that the closed tube sublimate is yellow.

Soluble in KOH and in aqua regia.

**Occurrence.** Like that of realgar.

### STIBNITE, $\text{Sb}_2\text{S}_3$

**Form.** Stibnite is found in prismatic or acicular crystals, in columnar or bladed aggregates, and in granular masses. Crystals are orthorhombic (bipyramidal class). Usual forms {110}, {010}, {111}, {113}, {121}. The habit is long prismatic with {110} as the dominant form ( $110:1\bar{1}0 = 89^\circ 34'$ ). Crystals are often highly modified and always vertically striated.

**Cleavage.** Perfect in one direction parallel to the side pinacoid (010). Also parting parallel to (001).

**H.** = 2.

**Sp. gr.**  $\pm 4.5$

**Color.** Lead gray. Luster, brilliant metallic on fresh surface. Streak, lead gray.

**Chemical Composition.** Antimony sulfid,  $\text{Sb}_2\text{S}_3$ ; (Sb = 71.4 per cent.).

**Blowpipe Tests.** On charcoal easily fusible (1) giving a greenish-blue flame, dense white fumes, and a white sublimate close to the assay. In the open tube gives  $\text{SO}_2$  and a white non-volatile sublimate ( $\text{Sb}_2\text{O}_3$ ) on the under side of the tube. In the closed tube gives a dark red sublimate of antimony oxysulfid ( $\text{Sb}_2\text{S}_2\text{O}$ ).

Decomposed by  $\text{HNO}_3$  with the separation of a white precipitate, ( $\text{HSbO}_3$ ).

**Uses.** Stibnite is the principal source of antimony.

**Occurrence.** 1. As a vein mineral associated with pyrite, sphalerite, galena, cinnabar, and realgar in a gangue of quartz, barite, or calcite. Prominent localities for specimens of stibnite are Felsőbanya, Hungary and Shikoku, Japan. At the latter locality magnificent crystals over a foot in length are found.



**Bismuthinite,  $\text{Bi}_2\text{S}_3$** 

**Form.** Bismuthinite is isomorphous with stibnite, and greatly resembles it.

**Cleavage.** In one direction parallel to the length.

**H.** = 2.

**Sp. gr.**  $\pm 6.4$

**Color.** Lead gray with a peculiar yellowish tarnish.

**Chemical Composition.** Bismuth sulfid,  $\text{Bi}_2\text{S}_3$ ; (Bi = 81.2 per cent.). Some varieties contain Se.

**Blowpipe Tests.** Easily fusible (1), giving on charcoal a metallic button (malleable, but brittle on the edges) and a yellow coating.

Soluble in  $\text{HNO}_3$ . On diluting the solution with water a white precipitate is formed.

**Occurrence.** 1. As a vein mineral associated with bismuth and chalcopyrite especially.

**Molybdenite,  $\text{MoS}_2$** 

**Form.** Molybdenite is usually found in foliated masses or in disseminated scales, and occasionally in hexagonal crystals of tabular habit.

**Cleavage.** One direction parallel to  $\{0001\}$ .

**H.** =  $1\frac{1}{2}$ .

**Sp. gr.**  $\pm 4.7$

**Color.** Bluish lead gray. The streak on glazed porcelain (or glazed paper) has a greenish tinge. Cleavages are flexible and sectile.

**Chemical Composition.** Molybdenum sulfid,  $\text{MoS}_2$ ; (Mo = 60.0 per cent.).

**Blowpipe Tests.** Infusible. On charcoal gives a white sublimate which is copper-red near the assay. Green  $\text{NaPO}_3$  bead in R.F., colorless in O.F.

Decomposed by  $\text{HNO}_3$  with the formation of a white sublimate ( $\text{MoO}_3$ ) which is soluble in  $\text{NH}_4\text{OH}$ .

**Uses.** Chief source of molybdenum, which is used as an alloy with steel.

**Occurrence.** 1. In pegmatites and surrounding rocks, especially granite.

2. In tin-stone veins with cassiterite, wolframite, topaz, etc.

3. As a contact mineral between limestones and granites associated with epidote, chalcopyrite, etc.

### Argentite, $\text{Ag}_2\text{S}$

**Form.** Occurs massive, incrusting, more rarely in rough crystals. The crystals are isometric, the only common form being the cube. Cubes are often arranged in parallel position.

**H.** =  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 7.3$

**Color.** Dark lead gray, almost black. Luster, metallic. Very sectile.

**Chemical Composition.** Silver sulfid,  $\text{Ag}_2\text{S}$ ; ( $\text{Ag}$  = 87.1 per cent.).

**Blowpipe Tests.** Easily fusible ( $1\frac{1}{2}$ ). On charcoal yields a malleable button of silver.

Soluble in  $\text{HNO}_3$  with the separation of S.  $\text{HCl}$  gives a white precipitate,  $\text{AgCl}$ , soluble in  $\text{NH}_4\text{OH}$ .

**Uses.** Argentite, called silver glance by miners, is an important ore of silver on account of the high silver content.

**Occurrence.** 1. As a vein mineral associated with other silver minerals. Freiberg, Saxony, furnishes fine specimens.

### GALENA, $\text{PbS}$

**Form.** Galena occurs in well-formed crystals as well as in cleavable and granular masses. Crystals are isometric (hexoctahedral class). The usual forms are the cube {100}, the octahedron {111}, more rarely the dodecahedron {110} and the tris-octahedron {221}. The habit is usually cubic, cubo-octahedral, or octahedral. Figs. 398 to 402 show a variety of habits. Contact or penetration twins with (111) as twin-plane and polysynthetic twins with (441) as twin-plane (see Fig. 239, p. 66) are sometimes observed.

**Cleavage.** Perfect cubic cleavage.

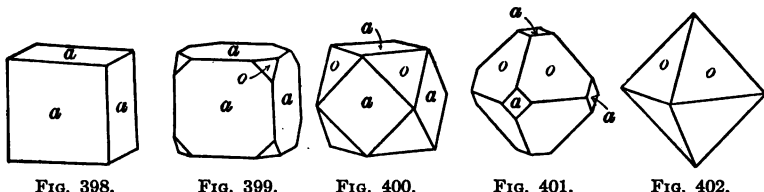
**H.** =  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 7.5$

**Color.** Lead gray, often tarnished. Metallic luster.

**Chemical Composition.** Lead sulfid,  $\text{PbS}$ ; ( $\text{Pb} = 86.6$  per cent.). May contain Zn, Ag, free sulfur, and other impurities.

**Blowpipe Tests.** Easily fusible at 2, giving on charcoal a malleable button, a yellow sublimate ( $\text{PbO}$ ) near the assay, and a white sublimate ( $\text{PbSO}_4$ ) farther from the assay.



Decomposed by  $\text{HCl}$  with the separation of  $\text{PbCl}_2$ , a white crystalline precipitate soluble in hot water. Decomposed by  $\text{HNO}_3$  with the separation of S and  $\text{PbSO}_4$ .

**Uses.** Galena is the most important ore of lead; argentiferous galena is one of the most important silver ores.

**Occurrence.** 1. As a vein mineral associated with sphalerite, chalcopyrite, pyrite, etc., often with barite as a gangue mineral. In the north of England galena occurs with fluorite, barite, calcite, and sphalerite in veins in Sub-carboniferous limestone.

2. As a metasomatic replacement of limestone.

3. In sedimentary rocks such as limestones, shales, and sandstones often associated with sphalerite. In southeastern Missouri galena is disseminated through Ordovician limestone.

### CHALCOCITE, $\text{Cu}_2\text{S}$

**Form.** Usually fine-grained compact masses, rarely in pseudo-hexagonal orthorhombic crystals, which are sometimes twinned.

**H.** =  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 5.7$

**Color.** Dark lead gray with black tarnish. Metallic luster. Chalcocite is sub-sectile, (*i.e.*, can be cut with a knife, but not so readily as argentite).

**Chemical Composition.** Cuprous sulfid,  $\text{Cu}_2\text{S}$ ; ( $\text{Cu} = 79.8$  per cent.). A little iron is usually present.

**Blowpipe Tests.** Fuses at 2. Unaltered in the closed tube. In R.F. on charcoal gives metallic copper.

Soluble in  $\text{HNO}_3$ , giving brown-red fumes, residue of S, and a green solution.

**Uses.** Chalcocite is a valuable ore of copper on account of the high percentage of copper. It is a prominent mineral in the ores at Butte, Montana.

**Occurrence.** 1. As a vein mineral along with other sulfids.

2. As a product of secondary enrichment. Butte, Montana.

3. As a replacement of lignite. Sierra Oscura Mts., New Mexico.

### SPHALERITE, $\text{ZnS}$

**Form.** Sphalerite crystallizes in the hextetrahedral class of the isometric system. Crystals are usually distorted and diffi-

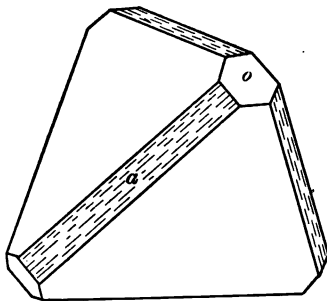


FIG. 403.

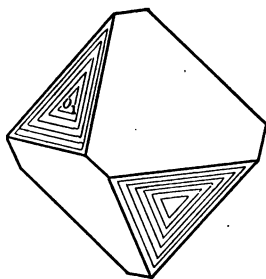


FIG. 404.

cult to decipher. The common habits are tetrahedral and dodecahedral, the usual forms being  $a\{100\}$ ,  $d\{110\}$ ,  $o\{111\}$ ,  $o_1\{1\bar{1}1\}$ , and  $m\{311\}$ . Figs. 403 and 404 represent typical crystals. Crystals are often twinned on the  $(111)$  face.

**Cleavage.** Prominent dodecahedral at angles of  $60^\circ$  and  $90^\circ$ .

**H.** =  $3\frac{1}{2}$  to 4.

**Sp. gr.**  $\pm 4.0$

**Color.** The color of sphalerite varies from white to black, depending upon the amount of iron present. The usual color is yellowish-brown or reddish-brown. The luster is adamantine, and the streak pale yellow to brown.

**Optical Properties.**  $n=2.37$ . Fragments are triangular, pale yellow, and isotropic (dark between crossed nicols). The high index of refraction accounts for the adamantine luster.

**Chemical Composition.** Zinc sulfid,  $\text{ZnS}$ ; ( $\text{Zn}=67.0$  per cent.). Iron replaces zinc isomorphously as shown in the formula  $(\text{Zn},\text{Fe})\text{S}$ . Cadmium is another common impurity. The rare elements indium and gallium were discovered in sphalerite. The following are typical analyses:

	Zn	Fe	S	Misc.
White: Franklin, New Jersey .....	67.5	.....	32.2	Cd = tr
Yellow: Schemnitz, Hungary .....	65.2	0.5	32.8	Cd = 1.5
Brown: Roxbury, Connecticut .....	63.4	3.6	33.4	
Dark brown: Westphalia .....	58.2	8.2	33.4	Cu = 0.1; Pb = tr
Black: Felsőbanya, Hungary .....	50.0	15.4	33.3	Cd = 0.3; Pb = 1.0

**Blowpipe Tests.** Difficultly fusible (5). On charcoal gives a white sublimate, which is yellow when hot. This sublimate heated intensely with cobalt nitrate solution gives a green color (cobalt zincate). The presence of Cd is indicated by an iridescent coating on charcoal.

Soluble in  $\text{HCl}$  with the evolution of  $\text{H}_2\text{S}$ .

**Uses.** Sphalerite is the most important ore of zinc. The Joplin district of southwest Missouri is the principal locality in this country.

**Occurrence.** 1. As a vein mineral associated with galena principally.

2. As an accessory mineral in sedimentary rocks.

**Alabandite, MnS**

**Form.** Usually massive, rarely in cubic crystals.

**Cleavage.** Imperfect cubic.

**H.** =  $3\frac{1}{2}$  to 4.

**Sp. gr.**  $\pm 4$

**Color.** Black or brownish-black with submetallic luster. The streak is olive-green, a distinctive test for this mineral.

**Optical Properties.** Fragments are square or irregular, translucent green, and dark between crossed nicols.  $n > 1.93$ .

**Chemical Composition.** Manganese sulfid, MnS; (Mn = 63.1 per cent.).

**Blowpipe Tests.** Fusible at 3. Unaltered in the closed tube. After roasting gives bead tests for Mn.

Soluble in HCl with the evolution of  $H_2S$ .

**Occurrence.** 1. As a vein mineral associated with rhodochrosite and sulfids. Tombstone, Arizona, is the only prominent American locality for this mineral.

**CINNABAR, HgS**

**Form.** Cinnabar often occurs in minute crystals in cavities. The crystals are hexagonal of variable habit. The common forms are  $\{10\bar{1}0\}$ ,  $\{10\bar{1}1\}$ ,  $\{0001\}$ , and  $\{40\bar{4}3\}$ . Cinnabar usually occurs disseminated through the rock and in massive and earthy forms.

**Cleavage.** Prismatic. Even in massive varieties reflections from minute cleavage planes may be seen.

**H.** =  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 8.0$

**Color.** Scarlet to dark red, black when impure. Luster, adamantine in typical specimens. Streak, vermilion.

**Optical Properties.**  $n_r(3.20) - n_a(2.85) = 0.35$ . Fragments are red, and irregular with high order interference colors. The very high index of refraction accounts for the adamantine luster. Basal sections of cinnabar are not dark between crossed nicols,

but become dark when one nicol is rotated  $325^\circ$  for a plate 1 mm. thick, using monochromatic red light. This property, possessed also by quartz, is called rotary polarization.

**Chemical Composition.** Mercuric sulfid,  $\text{HgS}$ ; ( $\text{Hg} = 86.2$  per cent.). Clay and organic matter are often present as impurities.

**Blowpipe Tests.** Volatile if pure. In the closed tube with dry soda cinnabar gives a sublimate of metallic mercury (little drops when rubbed with a wire).

Soluble in  $\text{HNO}_3$ .

**Uses.** Practically the only ore of mercury. The principal producing localities are Almaden in Spain, Idria in Austria, New Almaden and New Idria in California.

**Occurrence.** 1. In stock-work deposits, *i.e.*, scattered through the rock in stringers, etc., rather than in distinct veins. In the Coast Ranges of California cinnabar is associated with serpentine.

### Covellite, $\text{CuS}$

**Form.** Tabular hexagonal crystals are rare, the mineral usually occurring as a dissemination or incrustation.

**H.** =  $1\frac{1}{2}$  to 2.

**Sp. gr.**  $\pm 4.6$

**Color.** Deep indigo blue, almost black. Luster, metallic pearly to dull.

**Chemical Composition.** Cupric sulfid,  $\text{CuS}$ ; ( $\text{Cu} = 66.4$  per cent.).

**Blowpipe Tests.** Fusible at  $2\frac{1}{2}$ . In the closed tube gives a sublimate of sulfur (distinction from chalcocite). On charcoal burns with a blue flame, gives off  $\text{SO}_2$ , and leaves a button of copper.

Soluble in  $\text{HNO}_3$  to a green solution.

**Occurrence.** 1. A characteristic mineral of the zone of secondary sulfid enrichment. Butte, Montana, furnishes good specimens. In many mines it occurs as an incrustation on chalcopyrite.

**Millerite, NiS**

**Form.** Millerite occurs in acicular crystals and in fibrous crusts.

**H.** =  $3\frac{1}{2}$ .

**Sp. gr.**  $\pm 5.5$

**Color.** Brass yellow. Luster, metallic.

**Chemical Composition.** Nickel sulfid, NiS; (Ni = 64.7 per cent.). May also contain Co, Fe, and Cu.

**Blowpipe Tests.** Fusible at 2 to a magnetic globule which gives a borax bead in O.F., violet when hot.

Soluble in  $\text{HNO}_3$  to a green solution.

**Occurrence.** 1. As a vein mineral associated with cobalt and silver minerals.

2. As a secondary mineral with nickeliferous pyrrhotite. Gap Mine, Pennsylvania.

3. In sedimentary rocks in cavities penetrating calcite crystals. St. Louis, Mo. and Keokuk, Iowa.

**Niccolite, NiAs**

**Form.** Niccolite practically always occurs in a massive form without cleavage.

**H.** =  $5\frac{1}{2}$ .

**Sp. gr.**  $\pm 7.4$

**Color.** Pale copper red. Metallic luster.

**Chemical Composition.** Nickel arsenid, NiAs; (Ni = 43.9 per cent.). May also contain S, Sb, and Co.

**Blowpipe Tests.** Easily fusible (2) to a magnetic residue giving off arsin fumes.

Soluble in  $\text{HNO}_3$  to a green solution.

**Occurrence.** 1. As a vein mineral with cobalt and silver ores.

**PYRRHOTITE, FeS**

**Form.** Pseudohexagonal orthorhombic crystals of tabular habit are known, but are very rare. Usually massive and without cleavage.



**H.** = 4 (Pyrite is 6).

**Sp. gr.**  $\pm 4.6$

**Color.** Bronze-yellow. Luster, metallic. Pyrrhotite is attracted by the magnet.

**Chemical Composition.** Ferrous sulfid,  $\text{FeS}$ , with a little excess of sulfur. ( $\text{Fe} = 63.6$  per cent.). Often contains nickel up to 5 per cent.

**Blowpipe Tests.** Fuses at 3 to a magnetic globule, giving fumes of  $\text{SO}_2$ . In the closed tube gives little or no sulfur (distinction from pyrite).

Soluble in  $\text{HNO}_3$ .

**Uses.** The nickeliferous pyrrhotite of Sudbury, Canada, is an important ore of nickel.

**Occurrence.** 1. In basic igneous rocks. Some large deposits are due to magmatic segregation.

2. As a vein mineral.

3. In crystalline limestones.

## PYRITE GROUP—ISOMETRIC

Pyrite,  $\text{FeS}_2$ ; smaltite,  $\text{CoAs}_2$ ; chloanthite,  $\text{NiAs}_2$ ; cobaltite,  $\text{CoAsS}$ ; and gersdorffite,  $\text{NiAsS}$ , constitute an isomorphous group as they crystallize in the diploid class of the isometric system in cubes and pyritohedrons, and have a hardness of  $5\frac{1}{2}$  to  $6\frac{1}{2}$  and a specific gravity of 5 to 6.5. There are also intermediate compounds such as  $(\text{Co,Fe})\text{As}_2$ ,  $(\text{Ni,Fe})\text{As}_2$ , and  $(\text{Co,Fe})\text{AsS}$ . The general formula, then, can be written  $(\text{Fe,Co,Ni})(\text{As,Sb,S})_2$ .

### PYRITE, $\text{FeS}_2$

**Form.** Pyrite is often well crystallized and furnishes the typical example of the diploid class of the isometric system. The most common forms are the cube  $a\{100\}$ , pyritohedron  $e\{210\}$ , octahedron  $o\{111\}$ , diploid  $s\{321\}$ , diploid  $\{421\}$ , and trapezohedron  $\{211\}$ . The habit is nearly always cubic, pyritohedral, or octahedral. Figs. 405 to 412 represent typical crystals.

The cube faces are commonly striated as in Fig. 405. The  $\{hk0\}$  forms are so characteristic of pyrite that they are called pyritohedrons. Of these the pyritohedron  $\{210\}$  is the most common. Penetration twins of the pyritohedron with the  $a$ -axis as the twinning axis are occasionally found. (See Fig. 241, page 66).

$H_v = 6$  to  $6\frac{1}{2}$ .

Sp. gr.  $\pm 5.0$

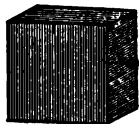


FIG. 405.

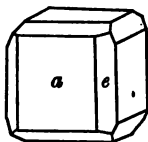


FIG. 406.

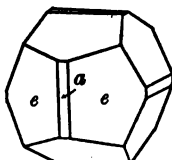


FIG. 407.

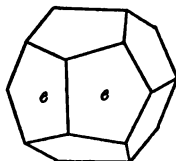


FIG. 408.

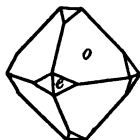


FIG. 409.

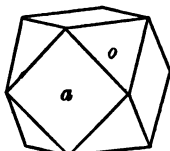


FIG. 410.

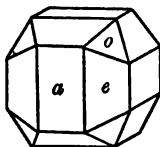


FIG. 411.

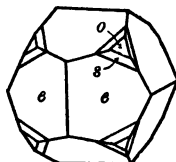


FIG. 412.

**Color.** Brass yellow. Luster, metallic. Streak, greenish to brownish-black.

**Chemical Composition.** Iron disulfid,  $\text{FeS}_2$ ; (Fe=46.6 per cent.). May contain Cu, Co, Ni, As, and Au. The copper is probably in the form of chalcopyrite. The following are typical analyses:

	Fe	S	Cu	Misc.
French Creek, Penn.....	44.2	54.1	0.05	Mn=0.5; Co=0.1; As=0.6
Arnsberg, Germany.....	46.4	51.4	1.0	
Cornwall, Penn.....	44.5	53.4	2.4	

**Blowpipe Tests.** Fusible at 3 to a magnetic globule. On charcoal pyrite burns with a blue flame, giving off  $\text{SO}_2$ . In the closed tube it gives a sublimate of sulfur and leaves a magnetic residue.

Insoluble in  $\text{HCl}$ , but soluble in  $\text{HNO}_3$  with the separation of S.

**Uses.** Pyrite is used extensively in the manufacture of sulfuric acid, which is the basis of many chemical industries. Pyrite is also an important low-grade copper ore at many localities, the copper being present as disseminated chalcopyrite. Pyrite is also often gold-bearing.

**Occurrence.** 1. As a vein mineral associated with other sulfids.

2. As an original mineral in igneous rocks.

3. As a secondary mineral in igneous rocks, especially in the country rock around ore-deposits.

4. As a dissemination in sedimentary rocks, such as shales and limestones, often replacing organisms.

5. As bedded deposits in metamorphic rocks.

6. As a contact mineral with hematite and magnetite. Lindgren states that the occurrence of iron sulfids and iron oxids together is characteristic of contact deposits.

### Cobaltite, $\text{CoAsS}$

**Form.** Cobaltite usually occurs in crystals, which are identical with those of pyrite, the cube, pyritohedron, and octahedron being the only common forms.

**H.** =  $5\frac{1}{2}$ .

**Sp. gr.**  $\pm 6.1$

**Color.** Reddish silver-white. Luster, metallic.

**Chemical Composition.** Cobalt arsenid-sulfid,  $\text{CoAsS}$ ; (Co = 35.4, As = 45.3, S = 19.3). Usually contains iron and occasionally nickel.

**Blowpipe Tests.** On charcoal gives arsin odor and fuses at  $2\frac{1}{2}$  to a gray, feebly magnetic globule, which colors a borax bead

deep blue. Unaltered in the closed tube (distinction from smaltite).

Soluble in  $\text{HNO}_3$  to a rose-colored solution with the separation of sulfur.

**Occurrence.** 1. In fahl-bands of schists and gneisses. Tunaberg, Sweden, is the principal locality.

**Smaltite,  $(\text{Co}, \text{Ni})\text{As}_2$**

**Form.** Smaltite is usually massive without any cleavage, but occasionally is found in cubic crystals.

**H.** =  $5\frac{1}{2}$ .

**Sp. gr.**  $\pm 6.2$

**Color.** Tin white to steel gray. Luster metallic.

**Chemical Composition.** Cobalt-nickel arsenid,  $(\text{Co}, \text{Ni})\text{As}_2$ , varying from  $\text{CoAs}_2$  ( $\text{Co} = 28.2$  per cent.) to  $\text{NiAs}_2$  ( $\text{Ni} = 28.1$  per cent.). Iron and sulfur are usually present in small amounts. The following analyses illustrate the range in composition.

	Co	Ni	Fe	As	S	Misc.
Atacama, Chile.....	24.1	1.2	4.1	70.8	0.1	Cu = 0.4
Wittichen, Germany.....	10.1	8.5	5.1	69.7	4.7	Cu = 0.9; Bi = 1.0
Schneeberg, Saxony.....	4.2	24.9	0.7	68.4	1.1	Bi = 0.2

**Blowpipe Tests.** On charcoal gives off arsin and fuses at  $2\frac{1}{2}$  to a magnetic globule, which colors the borax bead blue. In the closed tube gives an arsenic mirror if strongly heated.

Soluble in  $\text{HNO}_3$  to a rose-red solution.

**Uses.** Smaltite is the chief ore of cobalt. Schneeberg, Saxony, and Cobalt, Ontario, are the principal localities.

**Occurrence.** 1. As a vein mineral usually with silver and bismuth and in a gangue of calcite. Smaltite is often coated with erythrite, a cobalt arsenate called "cobalt bloom."

**MARCASITE GROUP—ORTHORHOMBIC**

The following minerals: marcasite,  $\text{FeS}_2$ ; arsenopyrite,  $\text{FeAsS}$ ; löllingite,  $\text{FeAs}_2$ ; glaucodot  $(\text{Co}, \text{Fe})\text{AsS}$ ; safflorite,  $\text{CoAs}_2$ ; and

rammelsbergite,  $\text{NiAs}_2$ , constitute an isomorphous group parallel to the pyrite group. They are orthorhombic in crystallization, have a hardness of 5 to  $6\frac{1}{2}$ , and are tin-white to brass-yellow in color. Only the first three of these minerals are considered as the others are rare.

### MARCASITE, $\text{FeS}_2$

**Form.** Marcasite occurs in orthorhombic crystals, in crystalline aggregates, and in rounded concretionary masses. Crystals are usually tabular in habit and often elongated in the direction of the  $a$ -axis. Figs. 413 to 415 represent typical crystals with

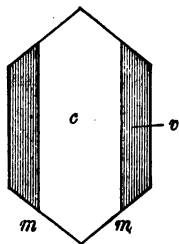


FIG. 413.

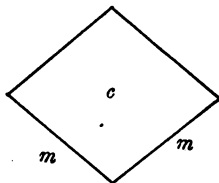


FIG. 414.

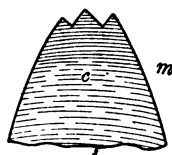


FIG. 415.

the forms:  $c\{001\}$ ,  $m\{110\}$ ,  $v\{013\}$ .  $mm(110:1\bar{1}0) = 74^\circ 55'$ . Twins with  $m\{110\}$  as twin-plane are common.

**H.** = 6 to  $6\frac{1}{2}$ .

**Sp. gr.**  $\pm 4.9$

**Color.** Pale brass yellow with a greenish tinge. Luster metallic.

**Chemical Composition.** Iron disulfid,  $\text{FeS}_2$ ; (Fe = 46.6 per cent.). Analyses often show small amounts of As.

**Blowpipe Tests.** The same as for pyrite.

**Uses.** If found in sufficient quantity, marcasite could be used in the manufacture of sulfuric acid.

**Occurrence.** 1. In sedimentary rocks, often in concretions.

2. As a vein mineral, but not so common as pyrite.

**ARSENOPYRITE,  $\text{FeAsS}$** 

**Form.** Arsenopyrite is found in well-formed crystals, as well as in disseminated grains and compact masses. The crystals are orthorhombic, similar in habit and angles to marcasite. Figs. 416 and 417 represent typical crystals with the forms  $m\{110\}$ ,  $c\{001\}$  and  $u\{014\}$ .

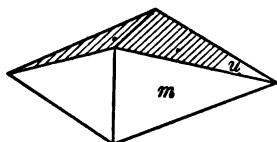


FIG. 416.

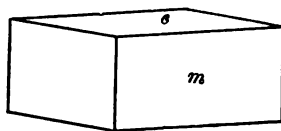


FIG. 417.

**H.** =  $5\frac{1}{2}$  to 6.

**Sp. gr.**  $\pm 6.0$

**Color.** Tin-white to light steel-gray. Luster, metallic.

**Chemical Composition.** Iron arsenid-sulfid,  $\text{FeAsS}$ ; ( $\text{Fe} = 34.3$ ,  $\text{As} = 46.0$ ,  $\text{S} = 19.7$ ). Often contains cobalt.

**Blowpipe Tests.** On charcoal fuses (at 2) to a magnetic globule and gives off arsin. In the closed tube on gentle heating gives a red sublimate ( $\text{AsS}$ ), but on further heating an arsenic mirror is formed.

Soluble in  $\text{HNO}_3$  with the separation of S.

**Uses.** Arsenopyrite is the chief source of the white arsenic ( $\text{As}_2\text{O}_3$ ) of commerce. At Deloro, Canada, arsenopyrite is a gold ore.

**Occurrence.** 1. As a vein mineral. Arsenopyrite is found in the quartz veins of the mother lode of California.

**Löllingite,  $\text{FeAs}_2$** 

**Form.** Usually massive, orthorhombic crystals similar to arsenopyrite being very rare.

**H.** =  $5\frac{1}{2}$ .

**Sp. gr.**  $\pm 7.1$

**Color.** Tin-white to steel-gray. Luster, metallic.

**Chemical Composition.** Iron arsenid,  $\text{FeAs}_2$  ( $\text{Fe} = 27.2$  per cent.). Usually contains some sulfur.

**Blowpipe Tests.** On charcoal fuses (at 2) to a magnetic globule and gives off arsin. In the closed tube gives an arsenic mirror. Usually gives a faint sulfur test on a silver coin.

Soluble in  $\text{HNO}_3$ .

**Occurrence.** 1 As a vein mineral.

### Sylvanite, $\text{AuAgTe}_4$

**Form.** Sylvanite occasionally is found in distinct monoclinic crystals but usually in branching crystal aggregates or in disseminated grains.

**Cleavage.** In one direction (parallel to 010).

**H.** = 2.

**Sp. gr.**  $\pm 8.0$

**Color,** silver-white to steel-gray. Luster, metallic. Brittle.

**Chemical Composition.** Gold and silver tellurid,  $\text{AuAgTe}_4$  ( $\text{Au} = 24.2$  per cent.;  $\text{Ag} = 13.3$  per cent.).

**Blowpipe Tests.** Easily fusible (at 1) on charcoal to a gray bead coloring the flame bluish-green and giving a white sublimate. With soda it is reduced to a pale yellow button. The powdered mineral dropped in hot concentrated  $\text{H}_2\text{SO}_4$  gives a purplish-red solution.

Soluble in aqua regia with the separation of  $\text{AgCl}$ .

**Uses.** An important ore of gold and silver. It is found in Boulder County, Colorado, in West Australia, and in Transylvania, Hungary.

**Occurrence.** 1. As a vein mineral. In Transylvania the veins occur in dacites.

### Calaverite, $\text{AuTe}_2$

**Form.** Calaverite usually occurs in small striated elongated crystals along seams. The crystals are complex monoclinic, some of the faces having very high indices.

**Fracture,** subconchoidal. No cleavage.

**H.** =  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 9.0$

**Color.** Pale brass yellow, resembling pyrite. Metallic luster.

**Chemical Composition.** Gold tellurid,  $\text{AuTe}_2$ ; (Au = 44. per cent.). Always contains some silver, usually from 2 to 4 per cent.

**Blowpipe Tests.** Easily fusible (at 1) on charcoal to a yellow button of gold, giving dense white fumes and coloring the flame bluish-green. With hot conc.  $\text{H}_2\text{SO}_4$  gives a purplish-red solution.

Soluble in aqua regia with the separation of a little  $\text{AgCl}$ .

**Uses.** An important ore of gold. At Cripple Creek, Colorado, it is the chief source of gold. It also occurs in West Australia. The name is derived from Calaveras County, California, but it is a very rare mineral at this locality.

**Occurrence.** 1 As a vein mineral. At Cripple Creek, fluorite is a common associate.



### 3. SULFO-SALTS

{ CHALCOPYRITE,	$\text{CuFeS}_2$
Stannite,	$\text{Cu}_2\text{FeSnS}_4$
BORNITE,	$\text{Cu}_5\text{FeS}_4$
Jamesonite,	$\text{Pb}_3\text{FeSb}_3\text{S}_{14}$
Bournonite,	$\text{PbCuSbS}_3$
{ Pyrargyrite,	$\text{Ag}_3\text{SbS}_3$
Proustite,	$\text{Ag}_3\text{AsS}_3$
TETRAHEDRITE,	$\text{Cu}_3\text{SbS}_3$
Stephanite,	$\text{Ag}_3\text{SbS}_4$
Polybasite,	$(\text{Ag,Cu})_{10}\text{Sb}_2\text{S}_{11}$
Enargite,	$\text{Cu}_3\text{AsS}_4$

Under the sulfo-salts are included certain compounds of sulfur, salts of hypothetical acids which may be derived from ordinary oxygen acids by replacing S for O, these two elements being very similar chemically.

Three classes of these compounds may be distinguished: (1) Sulfoferrites, derivatives of  $\text{H}_3\text{FeS}_3$ , analogous to ferrous acid,  $\text{H}_2\text{FeO}_3$ . (2) Sulfarsenites and sulfantimonites, derivatives of  $\text{H}_3\text{AsS}_3$  and  $\text{H}_3\text{SbS}_3$ , analogous to arsenious acid,  $\text{H}_3\text{AsO}_3$  and antimonous acid,  $\text{H}_3\text{SbO}_3$ . (3) Sulfarsenates and sulfantimonates, derivatives of  $\text{H}_3\text{AsS}_4$  and  $\text{H}_3\text{SbS}_4$ , analogous to arsenic acid,  $\text{H}_3\text{AsO}_4$ , and antimonic acid,  $\text{H}_3\text{SbO}_4$ .

There are also condensed acids derived from the above mentioned acids by the subtraction or addition of  $\text{H}_2\text{S}$ , just as condensed acids may be derived from oxygen acids by the subtraction or addition of  $\text{H}_2\text{O}$ . Thus chalcopyrite,  $\text{CuFeS}_2$ , is a salt of  $\text{HFeS}_2$  derived from  $\text{H}_3\text{FeS}_3$  ( $\text{H}_3\text{FeS}_3 - \text{H}_2\text{S} = \text{HFeS}_2$ ). Jamesonite is a salt of  $\text{H}_5\text{Sb}_3\text{S}_7$  ( $3\text{H}_3\text{SbS}_3 - 2\text{H}_2\text{S}$ ). Stephanite is a salt of  $\text{H}_5\text{SbS}_4$  ( $\text{H}_3\text{SbS}_3 + \text{H}_2\text{S}$ ). Polybasite is a salt of  $\text{H}_{10}\text{Sb}_2\text{S}_{11}$  ( $2\text{H}_3\text{SbS}_3 + 5\text{H}_2\text{S}$ ).

The sulfo-salts are sometimes considered as double sulfids. Thus tetrahedrite,  $\text{Cu}_3\text{SbS}_3$ , is written  $\text{Sb}_2\text{S}_3 \cdot 3\text{Cu}_2\text{S}$ .

About sixty sulfo-salt minerals are known, but most of them are rare.

### CHALCOPYRITE, $\text{CuFeS}_2$

**Form.** Chalcopyrite occurs in crystals, in masses, and disseminated through the rock. The crystals belong to the tetragonal system, scalenohedral class, but are pseudotetragonal and pseudo-octahedral in form. Fig. 418 represents a common type of crystal with the forms  $p\{111\}$  and  $z\{201\}$ . This resembles a tetrahedron, but is distinguished by the striations.

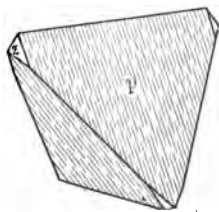


FIG. 418.

**H.** =  $3\frac{1}{2}$  to 4.

**Sp. gr.**  $\pm 4.2$

**Color.** Brass yellow often with iridescent tarnish. Metallic luster.

**Chemical Composition.** Cuprous sulfoferrite,  $\text{CuFeS}_2$ ; (Cu = 34.5 per cent.). Variations from this formula are usually due to admixed pyrite.

**Blowpipe Tests.** On charcoal fusible (at 2) to a magnetic globule which heated with soda gives a copper button. In the closed tube decrepitates and gives a sublimate of sulfur.

Soluble in  $\text{HNO}_3$  to a green solution with the separation of sulfur.

**Uses.** Chalcopyrite is the principal ore of copper.

**Occurrence.** 1. As a vein mineral associated with pyrite, galena, sphalerite, tetrahedrite, etc.

2. In basic igneous rocks with pyrrhotite, perhaps as a magmatic separation. Sudbury, Canada.

3. Disseminated through massive pyrite.

4. In fahlbands of schists and gneisses.

5. As a contact mineral with magnetite or hematite.

### Stannite, $\text{Cu}_2\text{FeSnS}_4$

**Form.** Stannite, though usually massive, is sometimes found in crystals which are similar to chalcopyrite in form.

**H. = 4.**      **Sp. gr.  $\pm 4.5$**

**Color.** Gray-bronze. **Metallic luster.**

**Chemical Composition.** Copper sulfoferrite-sulfostannite,  $\text{Cu}_2\text{FeSnS}_4$ , like chalcopyrite, but with half of the iron replaced by tin. (Sn = 27.6 per cent.). It usually contains zinc.

**Blowpipe Tests.** Fusible (at  $1\frac{1}{2}$ ) on charcoal, giving a straw-colored sublimate of  $\text{SnO}_2$  near the assay. With  $\text{Na}_2\text{CO}_3$  on charcoal (R.F.) gives metallic globules.

Soluble in  $\text{HNO}_3$  to a green solution with the separation of S and  $\text{H}_2\text{SnO}_3$  (white residue).

**Occurrence.** 1. As a vein mineral it occurs in Cornwall and Bolivia, where it is associated with other sulfo-salts and with cassiterite.

## BORNITE, $\text{Cu}_5\text{FeS}_4$

**Form.** Bornite occurs in masses, very rarely in rough cubic crystals.

**H. = 3. Sp. gr.  $\pm 5.1$**

**Color.** A brownish-red bronze with purple tarnish. Metallic luster.

**Chemical Composition.** Copper sulfoferrite,  $\text{Cu}_5\text{FeS}_4$ ; (Cu = 63.3 per cent.). Analyses vary widely due to intermixture with chalcopyrite and chalcocite.

**Blowpipe Tests.** Fusible (at  $2\frac{1}{2}$ ) on charcoal R.F. to a magnetic globule. In the closed tube gives a faint sublimate of sulfur.

Soluble in  $\text{HNO}_3$  to a green solution with the separation of S.

**Uses.** Bornite is an important ore of copper. It occurs at Butte, Montana, intimately associated with chalcocite.

**Occurrence.** 1. As a vein mineral associated with chalcocite and chalcopyrite.

2. As a contact mineral between limestones and igneous rocks.
3. As a product of secondary enrichment. Butte, Montana.

### Jamesonite, $\text{Pb}_4\text{FeSb}_6\text{S}_{14}$

**Form.** Jamesonite occurs in delicate capillary crystals and in columnar and compact masses.

**Cleavage.** In one direction transverse to the length of the crystals.

**H.** =  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 5.7$

**Color.** Lead-gray. Metallic luster.

**Chemical Composition.** Lead sulfantimonite,  $\text{Pb}_4\text{FeSb}_6\text{S}_{14}$ ; (Pb = 40.3 per cent.).

**Blowpipe Tests.** On charcoal easily fusible (at 1) giving white and yellow coatings. In the closed tube gives a yellow sublimate of sulfur and a dark-red sublimate of  $\text{Sb}_2\text{S}_3\text{O}$ . With soda on charcoal gives a lead button.

Soluble in HCl with the evolution of  $\text{H}_2\text{S}$ . On cooling the solution needle crystals of  $\text{PbCl}_2$  separate. Decomposed by  $\text{HNO}_3$  with the separation of a white residue.

**Occurrence.** 1. As a vein mineral.

### Bournonite, $\text{PbCuSbS}_3$

**Form.** Bournonite occurs in well-defined orthorhombic crystals and also in fine-grained masses. The crystals are usually twinned and bear some resemblance to cog-wheels, hence the name "cog-wheel ore."

**H.** =  $2\frac{1}{2}$  to 3.

**Sp. gr.**  $\pm 5.8$

**Color.** Dark gray to nearly black. Metallic luster.

**Chemical Composition.** Cuprous lead sulfantimonite,  $\text{PbCuSbS}_3$ .

**Blowpipe Tests.** On charcoal easily fusible (at 1) giving both a yellow and a white coating. The residue fused with soda gives a malleable button.

Decomposed by  $\text{HNO}_3$ , leaving a white residue.

**Occurrence.** 1. As a vein mineral associated with sulfids and other sulfo-salts.

### RUBY SILVER GROUP—HEXAGONAL

Pyrargyrite,  $\text{Ag}_3\text{SbS}_3$ , and proustite,  $\text{Ag}_3\text{AsS}_3$ , constitute an isomorphous group, for they both crystallize in the ditrigonal pyramidal class with almost identical interfacial angles. They both have a very high index of refraction and very strong double refraction. Pyrargyrite often contains As, while proustite often contains Sb, but the two compounds do not seem to mix in all proportions (Miers).

#### Pyrargyrite, $\text{Ag}_3\text{SbS}_3$

**Form.** Pyrargyrite often occurs in small well-defined crystals belonging to the ditrigonal pyramidal class. The habit is usually prismatic, the hexagonal prism  $\{11\bar{2}0\}$ , being the dominant form.

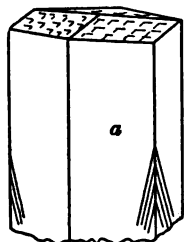


FIG. 419.

Opposite ends of the crystal are differently terminated. Fig. 419 represents a typical crystal, the striations indicating the hemimorphic character.

**H.** =  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 5.8$

**Color.** Dark red to black. Translucent red on thin edges. Streak purple-red. Luster metallic-adamantine.

**Optical Properties.**  $n_r(3.08) - n_a(2.88) = 0.20$ . Fragments are irregular and red in color, with high order interference colors.

**Chemical Composition.** Silver sulfantimonite,  $\text{Ag}_3\text{SbS}_3$ ; (Ag = 59.9 per cent.). Arsenic replaces antimony to some extent.

**Blowpipe Tests.** On charcoal fuses easily (at 1) to a globule of silver sulfid giving a white sublimate. This globule with soda in R.F. gives a silver button. Heated intensely in the closed tube gives a slight red sublimate.

Decomposed by  $\text{HNO}_3$  with the separation of sulfur and a white residue.

**Uses.** A valuable ore of silver.

**Occurrence.** 1. As a vein mineral often formed by secondary enrichment.

### Proustite, $\text{Ag}_3\text{AsS}_3$

**Form.** Crystals resemble those of pyrargyrite. Also massive and in crusts.

**H.** = 2 to  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 5.6$

**Color.** Red. Translucent in large pieces. Streak vermilion red. Luster, adamantine.

**Optical Properties.**  $n_\gamma(3.08) - n_\alpha(2.79) = 0.29$ . Fragments are irregular and red in color, with high-order interference colors.

**Chemical Composition.** Silver sulfarsenite,  $\text{Ag}_3\text{AsS}_3$ ; (Ag = 65.4 per cent.). Antimony often replaces part of the arsenic.

**Blowpipe Tests.** On charcoal fuses easily (at 1) to a globule and gives off fumes of arsin. The globule heated with soda gives a silver button. In the closed tube gives a yellow sublimate of  $\text{As}_2\text{S}_3$ .

Decomposed by  $\text{HNO}_3$  with the separation of sulfur. The solution treated with  $(\text{NH}_4)_2\text{MoO}_4$  and boiled, will yield a yellow precipitate of ammonium arsenomolybdate.

**Uses.** Proustite is a valuable ore of silver occurring with other silver minerals.

**Occurrence.** 1. As a vein mineral often formed by secondary enrichment. Guanajuato, Mexico and Chañarcillo, Chili, are prominent localities.

### TETRAHEDRITE, $\text{Cu}_3\text{SbS}_4$

**Form.** Tetrahedrite occurs in masses and also in crystals belonging to the hextetrahedral class of the isometric system. The common forms are the tetrahedron  $o\{111\}$ , the tristetrahe-

dron  $n\{211\}$ , and the dodecahedron  $d\{110\}$ . Figs. 420–423 represent typical crystals.

**H.** =  $3\frac{1}{2}$ –4.

**Sp. gr.**  $\pm 4.8$

**Color.** Dark iron-gray. Metallic luster. Brittle.

**Chemical Composition.** Copper sulfantimonite,  $\text{Cu}_3\text{SbS}_3$ ; (Cu = 46.8 per cent. Sb = 29.6, S = 23.0). The copper is often replaced

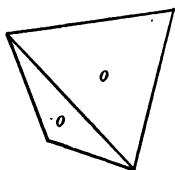


FIG. 420.

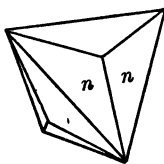


FIG. 421.

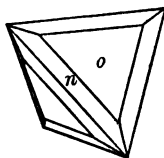


FIG. 422.

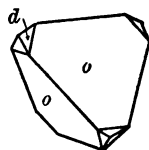


FIG. 423.

by Fe, Zn, Ag, or Hg and the antimony by arsenic. The following analyses illustrate the variation in chemical composition.

	Cu	Sb	S	As	Fe	Zn	Ag	Misc.
Fresney d'Oisans .....	45.4	28.8	24.5	tr	1.3	.....	.....	Pb = 0.1
Kapnik, Hungary .....	38.0	23.9	25.8	2.9	0.8	7.3	0.6	
Machetillo, Chili .....	36.7	20.7	25.3	6.5	1.2	6.9	2.9	
Cabarrus Co., N. C. ....	30.7	17.8	25.5	11.5	1.4	2.5	10.5	
Poracs, Hungary .....	32.8	30.2	24.9	.....	5.9	.....	0.1	Hg = 5.6

**Blowpipe Tests.** Easily fusible (at  $1\frac{1}{2}$ ) giving dense white fumes and a white sublimate near the assay. The residue heated with soda in R.F. gives metallic copper. In the closed tube gives a dark red sublimate ( $\text{Sb}_2\text{Sb}_2\text{O}$ ).

Soluble in  $\text{HNO}_3$  to a green solution with the separation of sulfur and a white residue,  $\text{HSbO}_3$ .

**Uses.** Tetrahedrite is an ore of copper and is known to miners as "gray copper." Argentiferous tetrahedrite or freibergite is an ore of silver.

**Occurrence.** 1. As a vein mineral often associated with chal-

copyrite. Cornwall, England, and Oruro, Bolivia, are prominent localities.

2. In fahlbands of schists, *fahlerz* being the German name for tetrahedrite.

### Stephanite, $\text{Ag}_5\text{SbS}_4$

**Form.** Stephanite occurs disseminated, compact massive, more rarely in crystals. The crystals are orthorhombic, but pseudo-hexagonal and short prismatic in habit.

**H.** =  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 6.2$

**Color.** Dark gray to black. Very brittle. Metallic luster.

**Chemical Composition.** Silver sulfantimonite,  $\text{Ag}_5\text{SbS}_4$ ; (Ag = 68.5 per cent.).

**Blowpipe Tests.** On charcoal easily fusible (at 1) to a globule giving dense fumes and a white sublimate of  $\text{Sb}_2\text{O}_3$ . The globule heated with soda R.F. gives a silver button.

Decomposed by  $\text{HNO}_3$  with the separation of sulfur and a white residue.

**Uses.** A valuable ore of silver. It was a prominent mineral in the Comstock Lode of Nevada. Stephanite is known to miners as "brittle silver."

**Occurrence.** 1. As a vein mineral.

### Polybasite, $(\text{Ag,Cu})_{16}\text{Sb}_2\text{S}_{11}$

**Form.** Polybasite usually occurs in monoclinic pseudo-hexagonal crystals of tabular habit. The basal pinacoid has triangular striations which distinguishes it from other similar minerals.

**H.** =  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 6.1$

**Color.** Iron black. Metallic luster.

**Optical Properties.**  $n > 1.93$ . The thinnest fragments are deep red translucent.

**Chemical Composition.** Silver-copper sulfantimonite  $(\text{Ag,Cu})_{16}\text{Sb}_2\text{S}_{11}$ ; (Ag = about 70 per cent.). Polybasite usually contains arsenic and grades into pearceite,  $(\text{Ag,Cu})_{16}\text{As}_2\text{S}_{11}$ .



**Blowpipe Tests.** On charcoal fuses easily (at 1) to a globule and gives a white sublimate. The globule heated with soda gives a metallic button. In order to get pure silver it is necessary to cupel the button.

Decomposed by  $\text{HNO}_3$  with the separation of sulfur and a white residue.

**Uses.** Polybasite is an ore of silver. It occurs at Tonopah, Nevada, and at several mines in Colorado.

**Occurrence.** 1. As a vein mineral, usually due to secondary enrichment.

### **Enargite, $\text{Cu}_3\text{AsS}_4$**

**Form.** Enargite occurs in columnar masses and also in prismatic orthorhombic crystals.

**Cleavage.** In two directions at angles of  $82^\circ$  to each other.

**H.** = 3.

**Sp. gr.**  $\pm 4.4$

**Color.** Dark gray to black.

**Chemical Composition.** Copper sulfarsenate,  $\text{Cu}_3\text{AsS}_4$ ; (Cu = 48.3 per cent.). Usually contains a little antimony and a little iron.

**Blowpipe Tests.** Easily fusible at 1, sulfur dioxide masking the odor of arsin. In the closed tube gives a sublimate of sulfur. In the open tube deposits minute octahedral crystals of  $\text{As}_2\text{O}_3$  with adamantine luster.

Soluble in  $\text{HNO}_3$ .

**Uses.** Enargite is an ore of copper, occurring at Butte, Montana, and at many localities in South America. Near Butte white arsenic is recovered from smelter smoke.

**Occurrence.** 1. As a vein mineral. At Tintic, Utah, enargite is the original source of several copper arsenate minerals.

## 4. HALOIDS

### *A. Normal anhydrous haloids*

<b>HALITE</b>	<b>NaCl</b>
Sylvite	KCl
Sal-ammoniac	$\text{NH}_4\text{Cl}$
Cerargyrite	AgCl
<b>FLUORITE</b>	$\text{CaF}_2$
Cryolite	$3\text{NaF} \cdot \text{AlF}_3$

### *B. Basic and hydrous haloids*

Atacamite	$\text{Cu}_2(\text{OH})_3\text{Cl}$
Carnallite	$\text{KMgCl}_3 \cdot 6\text{H}_2\text{O}$

The haloids comprise chlorids, bromids, iodids, and fluorids, which are salts of HCl, HBr, HI, and HF respectively. Comparatively few haloids occur in nature, but several of them are very common minerals. The haloid minerals may be assembled in two groups.

### **HALITE, NaCl**

**Form.** Halite occurs in crystals, and in cleavable, granular, and fibrous masses. Crystals are isometric, usually cubes (Fig. 424), sometimes hopper-shaped (Fig. 425), rarely in octahedrons or cubo-octahedrons (Fig. 426).

**Cleavage.** The perfect cubic cleavage is a marked feature of halite. A dodecahedral {110} parting is developed by pressure applied on the cube-edges by a hammer or in a vise (Fig. 307, page 106).

**H.** =  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 2.1$

**Color.** Colorless and white. Often reddish, gray, or deep blue in patches.

**Optical Properties.** Isotropic.  $n = 1.54$ . Recrystallizes from a water solution in squares, often hopper-shaped (Fig. 427), which are dark between crossed nicols and have low relief in oil of cloves.

**Chemical Composition.** Sodium chlorid,  $\text{NaCl}$ ; ( $\text{Na} = 39.4$  per cent.). Halite may contain  $\text{MgCl}_2$ ,  $\text{MgSO}_4$ ,  $\text{CaCl}_2$ , and  $\text{CaSO}_4$ . It is to these impurities that the deliquescence of table salt is due.

**Blowpipe Tests.** Fuses easily (1) giving an intense yellow flame. With  $\text{CuO}$  in  $\text{NaPO}_3$  bead gives an azure-blue flame.

Soluble in water.

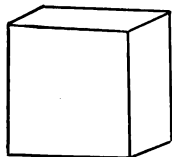


FIG. 424.

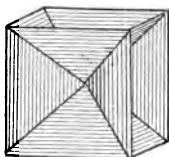


FIG. 425.

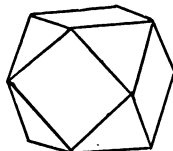


FIG. 426.

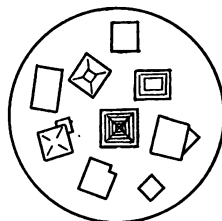


FIG. 427.

**Uses.** Halite is the chief source of sodium compounds used principally in the manufacture of soap and glass. It is also used extensively as table salt and as a preservative. Salt brines furnish bromin. Salt is obtained (1) directly by the mining of rocksalt as at Petite Anse, Louisiana, and Lyons, Kansas; (2) by pumping brine to surface and evaporating as at Syracuse, New York, and Hutchinson, Kansas; and (3) by solar evaporation as at Great Salt Lake, Utah.

**Occurrence.** 1. Occurs in beds associated with anhydrite, gypsum, and occasionally with other chlorids and sulfates. These deposits are formed by the evaporation of sea-water. Important localities are Stassfurt, Germany; Wieliczka, Poland; Cheshire, England; western New York; Saginaw, Michigan; and central Kansas.

### Sylvite, $\text{KCl}$

**Form.** Sylvite occurs in cleavable and granular masses and in well-formed cubic or cubo-octahedral (like Fig. 426) crystals. Etch-figures indicate that sylvite belongs to the gyroidal class of the isometric system.

**Cleavage.** Perfect cubic cleavage.

**Color.** Colorless or white. Taste, sharp saline.

**H.** = 2.

**Sp. gr.**  $\pm 2.0$

**Optical Properties.** Isotropic.  $n = 1.49$  ( $<$  oil of cloves). Recrystallizes from water solution in square crystals with a tendency toward skeleton crystals (Fig. 428).

**Chemical Composition.** Potassium chlorid, KCl; (K = 52.4 per cent.). It may contain NaCl.

**Blowpipe Tests.** Fuses easily ( $1\frac{1}{2}$ ) coloring the flame violet. With CuO in  $\text{NaPO}_3$  bead gives an azure-blue flame.

Soluble in water.

**Uses.** Used as a fertilizer and a source of potassium salts.

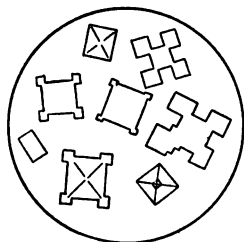


FIG. 428.—Sylvite recrystallized.

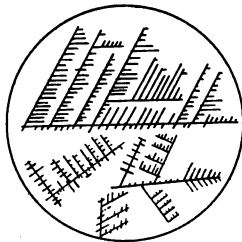


FIG. 429.—Sal-ammoniac recrystallized.

**Occurrence.** 1. In salt beds with halite, anhydrite, kainite, and carnallite. It is mostly a secondary mineral formed from carnallite ( $\text{KMgCl}_3 \cdot 6\text{H}_2\text{O}$ ). Stassfurt, Germany.

2. As a volcanic sublimate on lava. Vesuvius.

### Sal-ammoniac, $\text{NH}_4\text{Cl}$

**Form.** A rare mineral occurring as an incrustation. The usual crystals are distorted dodecahedrons. The biting taste is the easiest method of recognizing the mineral.

**H.** =  $1\frac{1}{2}$ .

**Sp. gr.**  $\pm 1.5$

**Tests.** Optically isotropic,  $n = 1.64$ . Recrystallizes from water solution in branching crystal aggregates (Fig. 429). Volatilizes

without fusion. Heated in the closed tube with KOH or CaO (made by heating calcite) it gives off  $\text{NH}_3$ . Soluble in water.

**Occurrence.** 1. Occurs as a volcanic sublimate. Vesuvius.

2. Occurs on coal-mine dumps (heat is due to spontaneous combustion). Leavenworth, Kansas.

### Cerargyrite, $\text{AgCl}$

**Form.** Cerargyrite usually occurs as a thin crust or seam, but small cubic crystals are also found.

**H.** =  $1\frac{1}{2}$ .

**Sp. gr.**  $\pm 5.5$

**Color.** Gray, greenish, or violet. Very sectile.

**Optical Properties.** Isotropic.  $n=2.06$ . May be hammered to a thin sheet which is translucent, but dark between crossed nicols. A few drops of  $\text{NH}_4\text{OH}$  will give minute octahedral crystals ( $\text{AgCl}$ ).

**Chemical Composition.** Silver chlorid,  $\text{AgCl}$ ; ( $\text{Ag}=75.3$  per cent.).

**Blowpipe Tests.** On charcoal fuses easily (1), giving a silver button. A fragment touched with a  $\text{NaPO}_3$  bead saturated with  $\text{CuO}$  gives an intense azure-blue flame.

Insoluble in acids, but soluble in  $\text{NH}_4\text{OH}$ .

**Uses.** An ore of silver in Idaho, Nevada, Mexico, and Chili. The miner's name is "horn-silver."

**Occurrence.** 1. A secondary mineral in the upper part of ore-deposits. It is formed by the action of chlorid-bearing waters on other silver minerals, and therefore is prominent in arid regions.

### FLUORITE, $\text{CaF}_2$

**Form.** Fluorite usually occurs in cleavable masses, but also often in distinct crystals. The crystallization is isometric (hexoctahedral class). Usual forms:  $a\{100\}$ ,  $f\{310\}$ ,  $t\{421\}$ ,  $d\{110\}$ ,  $o\{111\}$ . The habit is practically always cubic, the other forms being subordinate. Octahedral crystals are rare. At some localities apparent octahedra are built up of minute cubes

in parallel position. Figs. 430 to 433 represent typical crystals of fluorite. Fig. 433 is a penetration twin with the cube-diagonal as twin-axis. Vicinal faces with high indices such as  $\{32\cdot1\cdot0\}$  are often found on these crystals.

**Cleavage.** One of the most important characters of fluorite is the perfect octahedral cleavage. On a cube this will show as triangular faces at the vertices, or at least as cracks in this direction as in Fig. 433.

H. = 4.

Sp. gr.  $\pm 3.2$

**Color.** Usually some tint or shade of violet, green, or yellow. It is also white, colorless, and pink. The color is probably due to hydrocarbons. Some crystals from Cumberland are green by transmitted light, but blue by reflected light. This property,

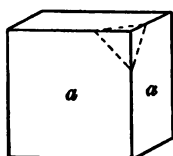


FIG. 430.

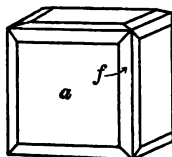


FIG. 431.

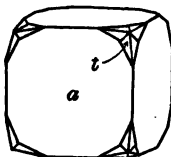


FIG. 432.

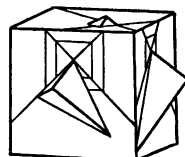


FIG. 433.

also possessed by some aniline colors such as red-ink, is known as fluorescence, a name derived from the mineral fluorite. Some varieties of fluorite are also phosphorescent, that is, after being heated, continue to emit light in the dark.

**Optical Properties.** Isotropic.  $n=1.43$ , hence high relief in oil of cloves. Fragments are triangular and dark between crossed nicols. (See Fig. 387.)

**Chemical Composition.** Calcium fluorid  $\text{CaF}_2$ ; (F=48.9 per cent.). Free fluorin has been detected in some fluorite. Fluorite is the only common compound of fluorin occurring in nature.

**Blowpipe Tests.** In the closed tube decrepitates. Fuses (at 3) to an enamel coloring the flame red.

Soluble in  $\text{H}_2\text{SO}_4$  with evolution of HF, which etches glass.

**Uses.** The main use of fluorite is a flux in iron smelting and

foundry work. Western Kentucky and southern Illinois are the principal sources of fluorite in this country. Minor uses are the manufacture of enamels, opalescent glass, and hydrofluoric acid. Moissan in his work on fluorin used vessels made of fluorite.

**Occurrence.** 1. As a vein mineral associated with galena, sphalerite, calcite, and barite. Typical localities are fissure veins in the limestone of western Kentucky and lead mines in the north of England, where magnificent museum specimens are found.

2. In tin-stone veins associated with cassiterite, apatite, topaz, and lepidolite. Zinnwald, Bohemia.

3. In limestones. St. Louis, Missouri.

### **Cryolite, $3\text{NaF} \cdot \text{AlF}_3$**

**Form.** Massive and in pseudo-cubic (monoclinic) crystals often in parallel position.

**Cleavage.** Imperfect in three directions at nearly right angles.

**H.** =  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 3.0$ .

**Color.** White, sometimes brown. Translucent.

**Optical Properties.**  $n_p = 1.36$ . Low relief in water (for water,  $n = 1.33$ ). Double refraction very weak. Fragments are roughly rectangular or irregular. Interference colors are first order gray.

**Chemical Composition.** Sodium aluminum fluorid,  $3\text{NaF} \cdot \text{AlF}_3$ ; (Al = 12.8 per cent., Na = 32.8).

**Blowpipe Tests.** Easily fusible (1) giving an intense yellow flame.

Soluble in  $\text{H}_2\text{SO}_4$  with the evolution of HF.

**Uses.** Formerly used as a source of aluminum, but now used as a bath in the electrolytic production of aluminum from bauxite. Also used in the manufacture of sodium and aluminum salts at Natrona, Pennsylvania. The mineral is shipped from Greenland.

**Occurrence.** 1. In granite-pegmatites. The most important locality is Ivigtut, in southern Greenland, where an immense vein-like mass of cryolite occurs in gneiss. At St. Peter's Dome in El Paso County, Colorado, cryolite occurs in veins in granite.

**Atacamite,  $\text{Cu}_2(\text{OH})_3\text{Cl}$** 

**Form.** Atacamite occurs in crystal aggregates, and in massive and incrusting forms. Crystals are orthorhombic and prismatic in habit.

**Cleavage** in one direction.

**H.** = 3 to  $3\frac{1}{2}$ .

**Sp. gr.**  $\pm 3.7$ .

**Color,** bright to dark green. **Streak,** pale green.

**Optical Properties.**  $n_r(1.88) - n_a(1.83) = 0.05$ . Fragments are prismatic with parallel extinction and are green in color.

**Chemical Composition.** Basic cupric chlorid,  $\text{Cu}_2(\text{OH})_3\text{Cl}$  or  $\text{CuCl}_2 \cdot 3\text{Cu}(\text{OH})_2$ ; ( $\text{H}_2\text{O} = 12.7$  per cent.).

**Blowpipe Tests.** The principal blowpipe test is the blue flame given *without the use of HCl*. Fusible at  $3\frac{1}{2}$ . In the closed tube gives water which has an acid reaction.

Soluble in acids.

**Occurrence.** 1. A secondary mineral found especially in the desert regions of Chili and Lower California.

**Carnallite,  $\text{KMgCl}_3 \cdot 6\text{H}_2\text{O}$** 

**Form.** Massive or granular. Crystals (orthorhombic) are very rare.

**Cleavage.** No cleavage, but has conchoidal fracture.

**H.** = 1.

**Sp. gr.**  $\pm 1.6$ .

**Color.** Colorless or reddish. **Luster,** greasy. Very deliquescent.

**Optical Properties.**  $n_r(1.49) - n_a(1.46) = 0.03$ . Recrystallized from water solution it forms in order (1) isotropic squares of KCl, (2) rectangular twinned crystals of  $\text{KMgCl}_3 \cdot 6\text{H}_2\text{O}$ , and (3) streaked aggregates of  $\text{MgCl}_2$  (Fig. 434).

**Chemical Composition.** Hydrous potassium magnesium chlorid  $\text{KMgCl}_3 \cdot 6\text{H}_2\text{O}$  or  $\text{KCl} \cdot \text{MgCl}_2 \cdot 6\text{H}_2\text{O}$ ; ( $\text{KCl} = 26.8$  per cent.) ( $\text{H}_2\text{O} = 39.0$  per cent.).



FIG. 434.



**Blowpipe Tests.** Fusible at  $1\frac{1}{2}$ , coloring the flame violet. With CuO in  $\text{NaPO}_3$  bead gives an azure-blue flame. Gives abundant water in the closed tube.

Soluble in water.

**Uses.** Carnallite is used as a fertilizer and in the manufacture of potassium salts. KCl crystallizes out of a water solution of carnallite.

**Occurrence.** 1. In salt beds associated with anhydrite, halite, sylvite, and kainite. Stassfurt, Prussia, is the only prominent locality.

## 5. OXIDS

QUARTZ,	SiO <sub>2</sub>
CHALCEDONY,	SiO <sub>2</sub>
ICE,	H <sub>2</sub> O
CUPRITE,	Cu <sub>2</sub> O
Zincite,	ZnO
Melaconite,	CuO
CORUNDUM,	Al <sub>2</sub> O <sub>3</sub>
HEMATITE,	Fe <sub>2</sub> O <sub>3</sub>
CASSITERITE,	SnO <sub>2</sub>
RUTILE,	TiO <sub>2</sub>
PYROLUSITE,	MnO <sub>2</sub>

Among the oxids are some of the most common and widely distributed minerals. The oxids of silicon are placed first and after them the monoxids R<sub>2</sub>O and RO, the sesquioxids, R<sub>2</sub>O<sub>3</sub>, and the dioxids, RO<sub>2</sub>, in order.

The minerals of the spinel group, sometimes considered as double oxids of the type RO·R<sub>2</sub>O<sub>3</sub>, are, in this book, placed in a separate division, the aluminates, ferrites, etc.

### QUARTZ, SiO<sub>2</sub>

**Form.** Crystals of quartz are very common, both large and small, loose and attached. There are crystalline aggregates of various kinds as well as massive, granular, and compact varieties.

Quartz crystallizes in the trigonal trapezohedral class of the hexagonal system.  $c=1.099$ . Usual forms:  $r\{10\bar{1}1\}$ ,  $z\{01\bar{1}1\}$ ,  $m\{10\bar{1}0\}$ ,  $s\{11\bar{2}1\}$ ,  $x\{51\bar{6}1\}$ . Interfacial angles:  $mr(10\bar{1}0:10\bar{1}1)=38^\circ 13'$ ;  $rz(10\bar{1}1:01\bar{1}1)=46^\circ 16'$ ;  $ms(10\bar{1}0:1\bar{1}21)=37^\circ 58'$ ;  $mx(10\bar{1}0:51\bar{6}1)=12^\circ 1'$ ;  $mm(10\bar{1}0:01\bar{1}0)=60^\circ 0'$ . Figs. 435-438 represent typical crystals. The habit varies from prismatic to pyramidal. The two rhombohedrons  $r$  and  $z$  are often in equal

combination (Figs. 435, 438) and are apparently a hexagonal bipyramid. The *s* face at alternate vertices proves the trigonal character. Figs. 375 and 376 are more complex (page 152).

**Cleavage**, practically absent (an imperfect cleavage parallel to *r* is occasionally noticed).

**H.** = 7.

**Sp. gr.**  $\pm 2.66$ .

**Color**, more often white or colorless, but may be any color. Luster, vitreous. Transparent to translucent, rarely opaque.

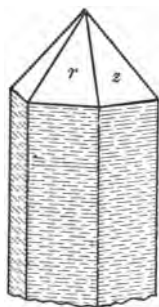


FIG. 435.

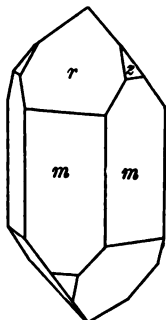


FIG. 436.

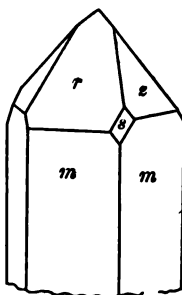


FIG. 437.

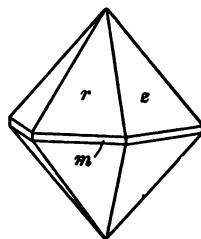


FIG. 438.

**Optical Properties.**  $n_r(1.553) - n_a(1.544) = 0.009$ . Double refraction rather weak. Fragments are irregular, with low relief in oil of cloves ( $n > \text{oil of cloves}$ ) and upper first order interference colors.

In thick basal ( $\perp$  to *c*-axis) sections quartz shows rotary polarization, *i.e.*, in monochromatic light a section only becomes dark by rotating one nicol. For red light the angle of rotation is  $13^\circ$  for each millimeter of thickness.

**Chemical Composition.** Silica or silicon dioxid,  $\text{SiO}_2$ . Variations in analyses are due to inclusions such as chlorite, tourmaline, rutile, etc.

**Blowpipe Tests.** Infusible even on the thinnest edges. When fused with an equal volume of soda, it effervesces and gives a colorless glass. Insoluble in a  $\text{NaPO}_3$  bead.

Insoluble in ordinary acids. Soluble in HF.

**Uses.** Quartz in the form of rock crystal, amethyst, and smoky quartz is used for ornamental purposes, in the form of rock crystal for optical instruments, in the form of sand for glass-making, and in the form of pulverized quartz for pottery and porcelain and as an abrasive.

**Occurrence.** 1. As a normal constituent of the acid igneous rocks (rhyolites and granites).

2. As an abnormal constituent of the basic igneous rocks, especially basalts (quartz-basalts).

3. As a vein mineral, often the gangue of ores. Quartz is the most common vein mineral.

4. As the chief constituent of sandstones and quartzites.

5. As a secondary mineral in various rocks, disseminated, in cavities, and impregnating the rock.

6. As petrifications and pseudomorphs after various minerals.

7. As the chief constituent of river and beach sands.

### CHALCEDONY, $\text{SiO}_2$

**Form.** Chalcedony occurs in mammillary, botryoidal, and stalactitic forms as well as massive and compact. Although chalcedony is never found in distinct crystals, it is crystalline as the examination of thin sections or fragments in polarized light will show.

**Fracture,** more or less conchoidal. No cleavage.

**H.** = 7.

**Sp. gr.**  $\pm 2.6$ .

**Color,** colorless, white, or any color, often banded and variegated. Red and brown varieties are called jasper and the banded and variegated varieties, agate. Translucent to opaque. Luster, waxy to dull.

**Optical Properties.**  $n_p = 1.537$ . Double refraction rather weak. Fragments are irregular with  $n$  about the same as oil of cloves. The aggregate structure with low order interference

colors in spots and streaks is highly characteristic of chalcedony and distinguishes it from quartz.

**Chemical Composition.** Silica,  $\text{SiO}_2$ . It often contains iron oxid.

**Blowpipe Tests.** Same as for quartz.

Chalcedony is more soluble in KOH than quartz.

**Uses.** Agate, chrysoprase (apple green translucent chalcedony), and jasper are used as ornamental stones.

**Occurrence.** 1. As a secondary mineral in seams and cavities of various rocks, especially the volcanic igneous rocks.

2. As chert or flint, and jasper, which occur in concretions, lenses, or layers in sedimentary rocks. In the Joplin district the zinc ores occur in a brecciated chert, which covers large areas. Cherts and flints are usually formed by the replacement of limestones by silica.

### Other Forms of Silica

Besides quartz, chalcedony, and opal (hydrated silica), there are a number of other forms of silica and at least one of these, tridymite, ranks as a separate mineral species. Tridymite is a biaxial pseudo-hexagonal mineral of tabular habit that occurs in the cavities of volcanic rocks.

It has recently been shown that there are two forms of quartz. The quartz of quartz veins formed from solutions is called  $\alpha$ -quartz, while the quartz of igneous rocks formed from molten magmas is called  $\beta$ -quartz.  $\alpha$ -quartz crystallizes in the trigonal trapezohedral class and has been formed below  $575^\circ \text{C}$ ., while  $\beta$ -quartz probably crystallizes in the hexagonal trapezohedral class and has been formed above  $575^\circ \text{C}$ .

### ICE, $\text{H}_2\text{O}$

Ice ranks as a mineral, as it is a naturally occurring substance of definite composition and crystal form. Ice belongs to the hexagonal system, but the crystal class is not certain. Fig. 440 illustrates hollow frost crystals observed by the author in Palo

Alto, California. Fig. 439 is a drawing of a photograph of a snow crystal taken by Mr. W. A. Bentley in Vermont.



FIG. 439.—Snow crystal.

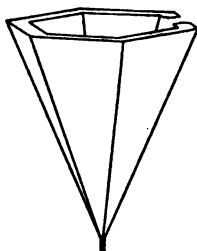


FIG. 440.—Frost crystal.

### CUPRITE, $\text{Cu}_2\text{O}$

**Form.** Cuprite is found in crystals, in crystalline aggregates, and in fine-grained masses. Crystals are isometric, the common forms being the cube, octahedron, and dodecahedron. The habit is usually determined by one of these forms. (Figs. 441–4.) Capillary cuprite found in Arizona proves to be elongate cubes.

**H.** =  $3\frac{1}{2}$ –4.

**Sp. gr.**  $\pm 6.0$ .



FIG. 441.

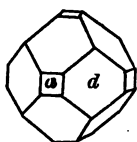


FIG. 442.

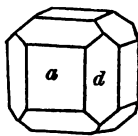


FIG. 443.

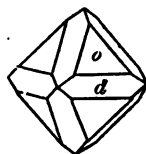


FIG. 444.

**Color.** Dark red to brownish-red. Translucent to opaque. Streak, brownish-red. Luster, metallic-adamantine.

**Optical Properties.** Isotropic.  $n=2.85$ . Fragments are irregular, translucent red, and dark between crossed nicols.

**Chemical Composition.** Cuprous oxid,  $\text{Cu}_2\text{O}$ ; ( $\text{Cu}=88.8$  per cent.). Iron oxid is the most frequent impurity.

**Blowpipe Tests.** On charcoal fuses ( $2\frac{1}{2}$ ) to a copper button.

Soluble in  $\text{HNO}_3$  to a green solution.

**Uses.** Cuprite is a valuable copper ore on account of the high percentage of copper. Bisbee, Arizona, is an important locality.

**Occurrence.** 1. As a secondary mineral in the oxidized zone derived from other copper compounds, especially native copper.

### Zincite, $\text{ZnO}$

**Form.** Zincite occurs in disseminated grains or foliated masses, very rarely in crystals (hexagonal).

**Cleavage** in one direction.

**H.** = 4 to  $4\frac{1}{2}$ .

**Sp. gr.** 5.5.

**Color,** deep red. **Streak,** orange. **Luster** metallic-adamantine.

**Optical Properties.**  $n > 1.93$ . Fragments are prismatic or irregular, yellow or orange, and non-pleochroic.

**Chemical Composition.** Zinc oxid,  $\text{ZnO}$ ; ( $\text{Zn} = 80.3$  per cent.). Usually contains manganese to the extent of about 4 per cent.

**Blowpipe Tests.** Infusible. Gives the bead tests for Mn and the  $\text{Co}(\text{NO}_3)_2$  test for Zn.

Soluble in  $\text{HCl}$ .

**Uses.** A mixture of zincite, franklinite, and willemite mined in Sussex Co., New Jersey, is used as a source of zinc white ( $\text{ZnO}$ ).

**Occurrence.** 1. Occurs with franklinite and willemite in a crystalline limestone in Sussex Co., New Jersey. This deposit is probably due to the metamorphism of a sedimentary limestone containing calamine with some manganese and iron minerals.

### Melaconite, $\text{CuO}$

**Form.** Melaconite is found massive or earthy, rarely in crystalline scales.

**H.** = 3 to 4.

**Sp. gr.**  $\pm 6.0$  (variable).

**Color,** black. **Luster,** dull or earthy. **Opaque.**

**Chemical Composition.** Cupric oxid,  $\text{CuO}$ ; ( $\text{Cu} = 79.8$  per cent.). It is often mixed with  $\text{MnO}_2$ .

**Blowpipe Tests.** Infusible. Gives flame and bead tests for copper.

Soluble in  $\text{HNO}_3$  to a green solution.

**Occurrence.** 1. As a secondary mineral in the oxidized zone of copper mines. (Not as common as cuprite.)

### HEMATITE GROUP—HEXAGONAL

Corundum and hematite form a perfect isomorphous group, although intermediate compounds are lacking. With them is sometimes placed ilmenite, but it is more properly considered a ferrous metatitanite,  $\text{FeTiO}_3$ . It belongs to a different crystal class, the trigonal rhombohedral class.

### CORUNDUM, $\text{Al}_2\text{O}_3$

**Form.** Corundum is found in rough loose crystals, in cleavable masses and disseminated through rock in small crystals or grains. The crystals belong to the scalenohedral class of the

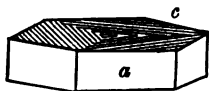


FIG. 445.

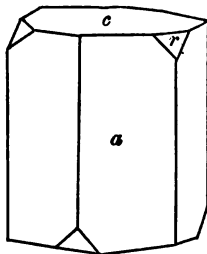


FIG. 446.

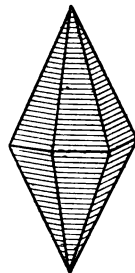


FIG. 447.

hexagonal system. Usual forms:  $c\{0001\}$ ,  $r\{10\bar{1}1\}$ ,  $a\{11\bar{2}0\}$ ,  $n\{22\bar{4}3\}$ . Interfacial angles:  $cr(0001:10\bar{1}1) = 57^\circ 34'$ ,  $rr(10\bar{1}1:\bar{1}101) = 93^\circ 56'$ ,  $cn(0001:22\bar{4}3) = 61^\circ 11'$ ;  $nn(22\bar{4}3:42\bar{2}3) = 51^\circ 58'$ . Habit prismatic (Fig. 446), tabular (Fig. 445), and steep pyramidal (Fig. 447). The trigonal character is shown by the



$r$  faces at alternate vertices and by the triangular striations on the base  $c$ .

**Cleavage.** There is often parting parallel to  $c$  and  $r$ . The rhombohedral parting greatly resembles cubic cleavage ( $rr = 93^\circ 56'$ ).

**H.** = 9.

**Sp. gr.**  $\pm 4.0$

**Color.** Bluish-gray is the most common color, but brown, red, pink, bright blue, and white colors are not at all rare. Usually translucent. Luster varies from vitreous to adamantine.

**Optical Properties.**  $n_r(1.767) - n_a(1.759) = 0.008$ . Double refraction rather low. Fragments are irregular with low order interference colors and index of refraction greater than methylene iodid. Large deep colored fragments or small crystals are often pleochroic.

**Chemical Composition.** Alumina or aluminum oxid,  $Al_2O_3$ ; ( $Al = 52.9$  per cent.). Emery is a dark-colored mixture of corundum with magnetite, hematite, or spinel.

**Blowpipe Tests.** Infusible. Heated with  $Co(NO_3)_2$  solution, it becomes deep blue.

Insoluble in acids. Decomposed by fusion with  $KHSO_4$ .

**Uses.** Certain varieties of corundum are valuable gems. Ruby, the transparent red corundum, is even more valuable than diamond. Sapphire is the blue transparent corundum. The best rubies come from Burma and the best sapphires from Ceylon.

Corundum is also used as an abrasive either as the pure cleavable mineral or as the mixture known as emery.

**Occurrence.** 1. In certain igneous rocks such as syenites and nepheline syenites in which an excess of  $Al_2O_3$  has crystallized out as corundum, just as an excess of  $SiO_2$  crystallizes as quartz in granites. At Craigmont, Ontario, corundum occurs in a syenite and is mined as an abrasive.

2. In peridotites along the borders of adjacent rocks. In North Carolina the country rocks are gneisses, but the mode of origin is doubtful.

3. In crystalline limestones (Burma, New York, New Jersey).

Emery is associated with limestone at Naxos, Greece, and perhaps is the metamorphic equivalent of bauxite.

4. In sands and gravels. The gem-bearing gravels of Ceylon furnish sapphire and other varieties of corundum.

### HEMATITE, $\text{Fe}_2\text{O}_3$

**Form.** Hematite is found in a variety of forms: small crystals in cavities, micaceous, fibrous, oölitic, compact, and earthy.

Crystals are hexagonal, usually tabular or low rhombohedral in habit (Figs. 448, 449). The island of Elba furnishes good crystals with the forms  $u\{10\bar{1}4\}$ ,  $r\{10\bar{1}1\}$  and  $n\{2\bar{2}43\}$  represented in plan by Fig. 450.

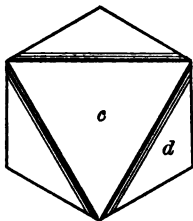


FIG. 448.

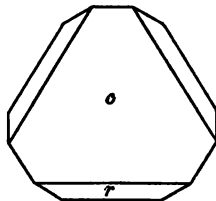


FIG. 449.

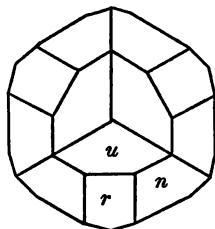


FIG. 450.

**H.** = 6.

**Sp. gr.**  $\pm 5.2$

**Color.** Iron-black to dark red. Streak, brownish-red. Luster, metallic to dull. Opaque, but translucent red in thin scales. These scales are dark between crossed nicols (basal sections).

**Chemical Composition.** Ferric oxid,  $\text{Fe}_2\text{O}_3$ ; (Fe = 70.0 per cent.). The iron is sometimes partly replaced by Ti and Mg.

**Blowpipe Tests.** Fusible with difficulty ( $5\frac{1}{2}$ ). On charcoal in R.F. becomes magnetic. Gives bead tests for iron.

Slowly soluble in concentrated HCl.

**Uses.** Hematite is the principal ore of iron, the Lake Superior district furnishing the principal supply. (See page 476.)

**Occurrence.** 1. As a metasomatic replacement of cherty

iron carbonate. This origin is assigned to the Lake Superior hematite.

2. As a metasomatic replacement of oölitic limestone producing oölitic hematite, the well known Clinton iron ore of New York and central Alabama.

3. As an alteration product of other iron minerals. The fibrous pencil-ore of England is supposed to be formed by the dehydration of limonite. Martite is a pseudomorph of hematite after octahedral crystals of magnetite.

4. As a pigment in many minerals and rocks, giving a red color. The red color of orthoclase, in many cases at least, is due to minute scales of hematite.

### RUTILE GROUP—TETRAGONAL

Cassiterite ( $\text{SnO}_2$ ) and rutile ( $\text{TiO}_2$ ) together with plattnerite ( $\text{PbO}_2$ ), polianite ( $\text{MnO}_2$ ), zircon ( $\text{ZrSiO}_4$  or  $\text{ZrO}_2 \cdot \text{SiO}_2$ ), and thorite ( $\text{ThSiO}_4$  or  $\text{ThO}_2 \cdot \text{SiO}_2$ ) are isomorphous, all being tetragonal and dioxids of tetravalent metals.

#### CASSITERITE, $\text{SnO}_2$

**Form.** Cassiterite is found in crystals, crystalline and reniform masses, pebbles, and grains (stream-tin). Crystals are tetragonal and prismatic or pyramidal in habit. Twins are common.

**H.** =  $6\frac{1}{2}$ .

**Sp. gr.**  $\pm 7.0$  (very heavy).

**Color**, black or brown. **Luster**, adamantine.

**Optical Properties.**  $n_\gamma = (2.09) - n_\alpha (1.99) = 0.10$ . Double refraction strong. Fragments are irregular with high order interference colors and high relief even in methylene iodid. Some varieties are pleochroic.

**Chemical Composition.** Tin oxid,  $\text{SnO}_2$ ; ( $\text{Sn} = 78.6$  per cent.).

**Blowpipe Tests.** Infusible. Fused with soda, sulfur, and a little powdered charcoal gives a metallic button and a straw-

colored coating near the assay. The coating heated with  $\text{Co}(\text{NO}_3)_2$  solution assumes a bluish-green color.

Insoluble in acids.

**Uses.** Cassiterite is practically the only source of tin. The Malay States lead in the production of tin.

**Occurrence.** 1. In tin-stone veins associated with topaz, wolframite, arsenopyrite, lepidolite, and fluorite, granite being the country rock. Zinnwald, Bohemia, is a prominent locality.

2. In greisen (quartz-muscovite rock) and other rocks affected by the intrusion of pegmatites, but rare in the pegmatites themselves.

3. In sands and gravels. (Stream-tin).

### RUTILE, $\text{TiO}_2$

**Form.** Rutile is found in embedded grains or crystals, as acicular inclusions or in a massive form. Crystals are tetragonal and usually prismatic in habit. Usual forms:  $p\{111\}$ ,  $e\{101\}$ ,

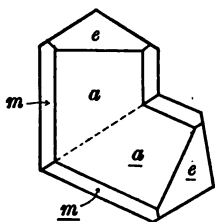


FIG. 451.

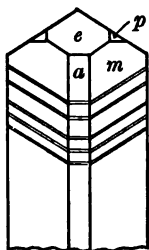


FIG. 452.

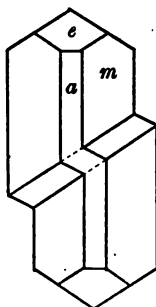


FIG. 453.

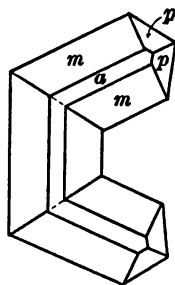


FIG. 454.

$a\{100\}$ ,  $m\{110\}$ . Interfacial angles:  $pm(111:100) = 47^\circ 40'$ ;  $ea(101:100) = 57^\circ 13'$ ;  $ee(101:011) = 45^\circ 2'$ . Figs. 451 to 454 represent various types of twinned crystals with  $e\{101\}$  as twin-plane.

**H.** = 6-6½.

**Sp. gr.**  $\pm 4.2$ .

**Color.** Red, brownish-red to black. Streak, pale brown. Luster, metallic-adamantine.

**Optical Properties.**  $n_r(2.90) - n_a(2.62) = 0.28$ . Fragments are yellow and irregular with high order interference colors and high relief even in methylene iodid.

**Chemical Composition.** Titanium oxid,  $TiO_2$ ; (Ti=60.0 per cent.). Iron is usually present.

**Blowpipe Tests.** Infusible. Gives a violet  $NaPO_3$  bead in R.F.

Insoluble in acids.

**Uses.** Rutile is used as coloring matter for porcelain and as a source of ferro-titanium. Nelson County, Virginia, is an important locality.

**Occurrence.** 1. As an accessory constituent of apatite veins occurring in gabbros. Norway.

2. As an accessory constituent of igneous rocks often occurring as acicular inclusions in quartz.

3. As a secondary mineral in various rocks such as gneisses, schists, and clays. The rutile is set free by the decomposition of titanium bearing silicates, especially the pyroxenes. Rutile is also an alteration product of titanite and occurs as a paramorph after brookite (an orthorhombic form of  $TiO_2$ ).

### PYROLUSITE, $MnO_2$

**Form.** Pyrolusite occurs in fibrous and columnar forms, in acicular crystals, in crusts, in masses, and along seams in dendritic forms. Crystals are prismatic but indistinct and perhaps always pseudomorphous after manganite.

**H.** = 1 to 2 (very soft). **Sp. gr.**  $\pm 4.8$ .

**Color,** black. **Streak,** black. **Luster,** metallic to dull. **Opaque.**

**Chemical Composition.** Manganese dioxid,  $MnO_2$ ; (Mn=63.2 per cent.). It usually contains about 2 per cent. of  $H_2O$ .

**Blowpipe Tests.** Infusible. In closed tube gives little or no water. Gives manganese bead tests.

Soluble in HCl with the evolution of chlorin.

**Uses.** Pyrolusite is one of the ores of manganese, but it is usually mixed with psilomelane or manganite. It is also used in the manufacture of chlorin and has other minor uses.

**Occurrence.** 1. In residual clays formed by the decomposition of limestone, there being a concentration of the manganese oxid. In many cases the pyrolusite is due to the dehydration of manganite.

2. Along seams of various rocks as a secondary mineral in dendritic forms.

## 6. ALUMINATES, FERRITES, ETC.

{	SPINEL,	MgAl <sub>2</sub> O <sub>4</sub> ,
	MAGNETITE,	FeFe <sub>2</sub> O <sub>4</sub> ,
	Franklinite,	(Zn,Mn)Fe <sub>2</sub> O <sub>4</sub> ,
	CHROMITE,	FeCr <sub>2</sub> O <sub>4</sub> ,
	Chrysoberyl,	BeAl <sub>2</sub> O <sub>4</sub> ,

These minerals are sometimes considered as oxides, but they may also represent salts of certain unfamiliar acids. Spinel is magnesium metaluminate derived from  $\text{HAlO}_2$  ( $\text{H}_3\text{AlO}_3 - \text{H}_2\text{O}$ ). Magnetite is ferrous metaferrite, iron acting both as an acid and as a base. Chromite is ferrous metachromite, derived from  $\text{HCrO}_2$  ( $\text{H}_3\text{CrO}_3 - \text{H}_2\text{O}$ ).

### SPINEL GROUP—ISOMETRIC

All the above enumerated minerals except chrysoberyl belong to the spinel group, which is one of the best known examples of isomorphism, for many intermediate compounds exist. The minerals of this group are isometric and usually crystallize in octahedrons. Besides the minerals mentioned there are also hercynite ( $\text{FeAl}_2\text{O}_4$ ), gahnite ( $\text{ZnAl}_2\text{O}_4$ ), magnesioferrite ( $\text{MgFe}_2\text{O}_4$ ), and jacobsite ( $\text{MnFe}_2\text{O}_4$ ). The general formula, then, is:  $(\text{Mg,Fe,Mn,Zn})(\text{Al,Fe,Cr,Mn})_2\text{O}_4$ . The following analyses, which have been recalculated in the present form from the original analyses, illustrate the range and variation in composition.

Analyses of Minerals of the Spinel Group

	Mg	Fe''	Mn''	Zn	Al <sub>2</sub> O <sub>4</sub>	Fe <sub>2</sub> O <sub>4</sub>	Mn <sub>2</sub> O <sub>4</sub>	Cr <sub>2</sub> O <sub>4</sub>	Misc.
Spinel.....	14.8	3.6	.....	.....	80.2	1.8	.....	.....	.....
Spinel, picotite...	14.5	2.9	.....	.....	62.0	12.5	.....	7.9	.....
Spinel, pleonaste..	7.8	18.3	.....	.....	72.3	.....	.....	.....	.....
Magnetite .....	1.3	21.5	0.3	.....	1.3	75.4	.....	0.6	.....
Franklinite .....	.....	.....	8.2	17.5	.....	70.0	4.8	.....	.....
Chromite .....	.....	27.3	.....	.....	11.1	.....	.....	56.8	SiO <sub>2</sub> =2.9
Chromite * .....	8.4	9.6	0.1	.....	14.1	4.2	.....	62.7	.....

\* After deducting 3.3% serpentine.

**SPINEL,  $MgAl_2O_4$** 

**Form.** Spinel is practically always found in crystals or grains, usually disseminated, but sometimes loose in sands and gravels. Crystals are isometric, the octahedron being the only common form (Fig. 455). Contact-twins with  $\{111\}$  as twinning plane are so common that this twin-law is known as the spinel law (Fig. 456).

**H.** = 8.

**Sp. gr.**  $\pm 3.6$ .

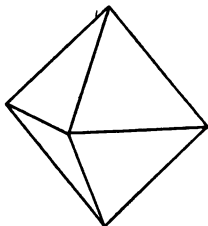


FIG. 455.

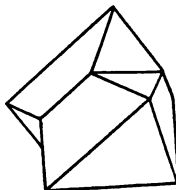


FIG. 456.

**Color,** black and dark shades of gray, brown, and green; also red and blue. Usually translucent. Luster, sub-adamantine.

**Optical Properties.** Isotropic.  $n=1.72$ . Fragments are irregular and dark between crossed nicols. The usual color of the fragments is green (pleonaste) and coffee-brown (picotite).

**Chemical Composition.** Magnesium metaluminate,  $MgAl_2O_4$ , or  $MgO \cdot Al_2O_3$ ; (Mg=17 per cent.). The magnesium is often replaced by ferrous iron and the aluminum by chromium and ferric iron. The iron-bearing spinel is called pleonaste and the chrome-bearing spinel, picotite.

**Blowpipe Tests.** Infusible, but the color may change on heating. Turns blue when heated with cobalt nitrate solution.

Insoluble in hydrochloric and nitric acids. Decomposed by fusion with potassium acid sulfate.

**Uses.** A red variety called spinel-ruby is used as a gem.



**Occurrence.** (1) As a contact mineral in crystalline limestone associated with phlogopite, chondrodite, corundum, and graphite. Amity, New York, is a prominent locality.

(2) As an accessory mineral in various igneous and metamorphic rocks. Pleonaste occurs with emery; picotite, with serpentine.

(3) In the gem bearing gravels of Ceylon. (Ruby spinel.)

### MAGNETITE, $\text{FeFe}_2\text{O}_4$ ( $\text{Fe}_3\text{O}_4$ )

**Form.** Magnetite occurs in loose and attached crystals, in compact and granular masses, and in the form of sand. Crystals belong to the hexoctahedral class of the isometric system. The only common forms are the octahedron *o*, the dodecahedron *d*, and the trapezohedron *m*{311}. The habit is octahedral, more rarely dodecahedral, but almost never cubic. Figs. 457, 458, and 459 represent typical crystals.

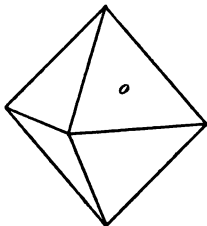


FIG. 457.

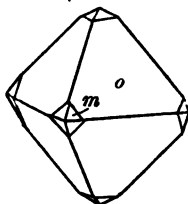


FIG. 458.

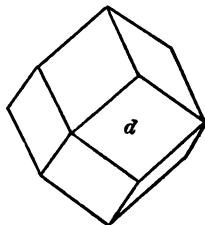


FIG. 459.

**Cleavage.** Some specimens have octahedral parting.

**H.** = 6.

**Sp. gr.**  $\pm 5.1$ .

**Color,** black. Opaque. Metallic luster. Strongly attracted by the magnet and sometimes is a magnet itself (*lodestone*).

**Chemical Composition.** Ferrous metaferrite,  $\text{FeFe}_2\text{O}_4$  or  $\text{FeO} \cdot \text{Fe}_2\text{O}_3$  (Total iron = 72.4 per cent.). May contain Mg, Mn, or Ti.

**Blowpipe Tests.** Fusible with difficulty ( $5\frac{1}{2}$ ). Gives bead tests for iron.

Soluble in concentrated HCl.

**Uses.** Magnetite is an important ore of iron, mined in New York, New Jersey, and Pennsylvania. In Scandinavia it is the principal iron ore.

**Occurrence.** (1) A very common and widely distributed accessory constituent of igneous rocks.

(2) In ore-deposits due to magmatic segregation. The Scandinavian magnetite has this origin.

(3) As a contact mineral between igneous rocks and limestones, often occurring with pyrite.

(4) In lenses and layers in schists and gneisses.

(5) As an alteration product of iron-bearing silicates in more or less altered igneous rocks.

(6) As the main constituent of the so-called black sands which are prominent on the Pacific Coast.

### Franklinite, $(\text{Zn,Mn})\text{Fe}_2\text{O}_4$

**Form.** Franklinite occurs in disseminated crystals or in granular aggregates. The crystals are usually octahedrons, modified by the dodecahedron (like Fig. 444, p. 309).

**H.** = 6.

**Sp. gr.**  $\pm 5.1$ .

**Color,** black. **Opaque.** Luster, metallic. Streak, dark brown. Slightly magnetic.

**Chemical Composition.** Zinc-manganese metaferriite,  $(\text{Zn,Mn})\text{Fe}_2\text{O}_4$  or  $(\text{Zn,Mn})\text{O} \cdot \text{Fe}_2\text{O}_3$ ; ( $\text{ZnO}$  = 17 to 25 per cent.,  $\text{MnO}$  = 10 to 16 per cent.). Some analyses show ferrous iron and manganic manganese. A typical analysis is given on page 318.

**Blowpipe Tests.** Infusible. In O.F. the borax bead is amethyst (Mn), while in R.F. it is green (Fe). On charcoal with soda gives a white coating of  $\text{ZnO}$  and a magnetic residue.

Soluble in  $\text{HCl}$  with the evolution of a little chlorine.

**Uses.** Franklinite mined in Sussex County, New Jersey, is used for the production of zinc white. The residue is used for the production of spiegeleisen, an iron-manganese alloy.

**Occurrence.** 1. In crystalline limestone with willemite, zincite, and rhodonite. Sussex County, New Jersey, is practically the only locality for this mineral. This deposit was probably formed by the metamorphism of a sedimentary limestone containing calamine and some manganese mineral.

### CHROMITE, $\text{FeCr}_2\text{O}_4$

**Form.** Chromite occurs disseminated and in compact masses, rarely in octahedral crystals.

**H.** =  $5\frac{1}{2}$ .

**Sp. gr.**  $\pm 4.4$ .

**Color,** black. **Streak,** dark brown. **Luster,** submetallic or metallic. **Opaque.**

**Optical Properties.** Isotropic  $n > 1.93$ . Thin fragments are irregular, usually translucent brown, and dark between crossed nicols.

**Chemical Composition.** Ferrous metachromite,  $\text{FeCr}_2\text{O}_4$ , or  $\text{FeO} \cdot \text{Cr}_2\text{O}_3$  (Fe = 24.8 per cent.). Mg, Al, and ferric Fe are usually present. Two typical analyses are given on page 318.

**Blowpipe Tests.** Infusible. Gives chromium bead tests. Fused with soda gives a magnetic mass.

Insoluble in acids. Decomposed by soda with the formation of sodium chromate, which is soluble in water.

**Uses.** Chromite is the only source of the salts of chromium such as potassium chromate, potassium dichromate, and lead chromate. Chromite bricks are used as a furnace-lining for certain kinds of smelting. Ferro-chrome is an alloy used in making chrome-steel.

**Occurrence.** (1) In peridotites as an original constituent. Ore-deposits may be due to magmatic segregation.

(2) In serpentine rocks probably derived from chromium-bearing olivine in the process of the serpentinization of peridotite.

### Chrysoberyl, $\text{BeAl}_2\text{O}_4$

**Form.** Chrysoberyl usually occurs in distinct orthorhombic crystals which are often pseudohexagonal on account of twinning.

Fig. 460 is a drawing of a penetration trilling with slight reentrant angles.

$H. = 8\frac{1}{2}$ .

Sp. gr.  $\pm 3.7$ .

**Color** usually green. One variety (alexandrite) is emerald-green, but red by transmitted light.

**Optical Properties.**  $n_r(1.75) - n_a(1.74) = 0.01$ . Fragments are irregular with first-order interference colors.

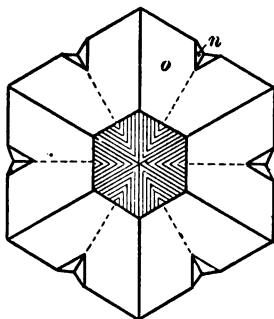


FIG. 460.

**Chemical Composition.** Beryllium metaluminate,  $\text{BeAl}_2\text{O}_4$ , or  $\text{BeO} \cdot \text{Al}_2\text{O}_3$ . (Be = 7.1 per cent.)

**Blowpipe Tests.** Infusible. Heated with cobalt nitrate solution gives a deep blue color. Chrysoberyl, if finely powdered, is soluble in a  $\text{NaPO}_3$  bead.

Insoluble in acids.

**Uses.** Several varieties of chrysoberyl are used as gems. Alexandrite, mentioned above, is a valuable gem. True cat's eye is a fibrous variety of chrysoberyl.

**Occurrence.** 1. In granite, gneisses, and schists.

2. In sands and gravels. Ceylon.

## 7. HYDROXIDS

OPAL,	$\text{SiO}_2 \cdot x\text{H}_2\text{O}$
Stibiconite,	$\text{Sb}_2\text{O}_4 \cdot \text{H}_2\text{O}$
{ Diaspore,	$\text{Al}(\text{OH})_3 \cdot \text{Al}_2\text{O}_3$
{ Göthite,	$\text{Fe}(\text{OH})_3 \cdot \text{Fe}_2\text{O}_3$
MANGANITE,	$\text{Mn}(\text{OH})_3 \cdot \text{Mn}_2\text{O}_3$
LIMONITE,	$2\text{Fe}(\text{OH})_3 \cdot \text{Fe}_2\text{O}_3$
BAUXITE,	$\text{Al}_2\text{O}_3 \cdot x\text{H}_2\text{O}$
BRUCITE,	$\text{Mg}(\text{OH})_2$
PSILOMELANE,	$4\text{MnO}_2 \cdot (\text{Ba}, \text{K}_2)\text{O} \cdot \text{H}_2\text{O} (?)$
WAD,	$\text{MnO}_2 + \text{H}_2\text{O}$ (impure)

The hydroxids or hydrous oxids are in part normal hydroxids such as  $\text{Mg}(\text{OH})_2$ . Others may be derived by subtracting water from the normal compounds. For example,  $2\text{Fe}(\text{OH})_3 - \text{H}_2\text{O} = \text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$ , göthite;  $4\text{Fe}(\text{OH})_3 - 3\text{H}_2\text{O} = 2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ , limonite. The formulæ may be written in various ways. Limonite may be written  $2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ ,  $\text{H}_6\text{Fe}_4\text{O}_9$ ,  $\text{Fe}_4\text{O}_3(\text{OH})_6$ , or  $2\text{Fe}(\text{OH})_3 \cdot \text{Fe}_2\text{O}_3$ .

### OPAL, $\text{SiO}_2 \cdot x\text{H}_2\text{O}$

**Form.** Opal usually occurs in seams and cavities, but is also disseminated and massive. It is one of the few minerals that never crystallizes. The glassy variety, called hyalite, has a botryoidal or mammillary surface.

**Fracture,** conchoidal. No cleavage. Very brittle.

**H.** =  $5\frac{1}{2}$  to  $6\frac{1}{2}$ .

**Sp. gr.**  $\pm 2.1$  (very light).

**Color,** white, colorless, or almost any color. Usually translucent. Luster, more or less greasy. Hyalite is vitreous.

**Optical Properties.** Isotropic.  $n = 1.45$ . Fragments are irregular, dark between crossed nicols, and have high relief in oil of cloves with index of refraction less than oil of cloves (Becke test). Opal is often intimately mixed with chalcedony.

**Chemical Composition.** Hydrated silica,  $\text{SiO}_2 \cdot x\text{H}_2\text{O}$ , with water varying from 3 to 12 per cent. The following are typical analyses:

	$\text{SiO}_2$	$\text{H}_2\text{O}$	$\text{Al}_2\text{O}_3$	$\text{Fe}_2\text{O}_3$	$\text{CaO}$	$\text{MgO}$
Waltzsch, Bohemia.....	95.5	3.0	.....	0.8	0.2	.....
Washington Co., Ga.....	91.9	5.8	1.4	.....	.....	0.9
Faroe Islands.....	88.7	8.0	1.0	.....	0.5	1.5
Meronitz, Bohemia.....	83.7	11.5	.....	3.6	1.6	0.7

**Blowpipe Tests.** Infusible, but becomes opaque. In the closed tube yields water.

Insoluble in the ordinary acids. Soluble in HF and also soluble in KOH.

**Uses.** The opal with play of colors known as precious opal and also the red or fire-opal are well known gems. The best precious opals are found in New South Wales and in Hungary, while fire-opal is found principally in Mexico.

**Occurrence.** 1. As a secondary mineral in cavities and along the seams of igneous rocks. Fire-opal and precious opal occur principally in trachyte, while hyalite occurs in any of the igneous rocks.

2. As siliceous sinter or geyserite formed around the hot springs and geysers. Yellowstone National Park is a prominent locality.

3. As the principal constituent of diatomaceous earth. Diatoms and radiolaria secrete casts of opal silica.

### Stibiconite, $\text{Sb}_2\text{O}_4 \cdot \text{H}_2\text{O}$

**Form.** Stibiconite occurs massive or as a coating. It is never found crystallized, but is sometimes pseudomorphous after stibnite.

**H.** = 4 to 5.

**Sp. gr.**  $\pm 5.2$ .

**Color,** pale yellow. **Luster,** dull.

**Optical Properties.**  $n > 1.65$ ,  $n < 1.74$ . Fragments, irregular, pale yellow, mostly isotropic.

**Chemical Composition.** Hydrated antimony tetroxid,  $\text{Sb}_2\text{O}_4 \cdot \text{H}_2\text{O}$ ; (Sb = 74.5 per cent.,  $\text{H}_2\text{O}$  = 5.6 per cent.).

**Blowpipe Tests.** Infusible. In the closed tube gives water. Insoluble in HCl.

**Occurrence.** 1. A secondary mineral often found with stibnite and resulting from its oxidation.

### Diaspore, $\text{Al}(\text{OH})_3 \cdot \text{Al}_2\text{O}_3$

**Form.** Diaspore usually occurs in bladed crystal aggregates, rarely in distinct orthorhombic crystals.

**Cleavage,** in one direction (010) parallel to the length.

**H.** =  $6\frac{1}{2}$ .

**Sp. gr.**  $\pm 3.4$ .

**Color,** colorless, white, gray, and pale colors. Luster, pearly to vitreous.

**Optical Properties.**  $n_g = 1.722$  Fragments are prismatic with bright interference colors, parallel extinction, and negative elongation.

**Chemical Composition.** Aluminum hydroxid,  $\text{Al}(\text{OH})_3 \cdot \text{Al}_2\text{O}_3$  or  $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$ ; ( $\text{H}_2\text{O}$  = 15.0 per cent.).

**Blowpipe Tests.** Infusible. When heated with cobalt nitrate solution it becomes blue. In the closed tube decrepitates and gives water at a high temperature.

Insoluble in acids.

**Occurrence.** 1. Occurs with corundum or emery and with margarite. Chester, Massachusetts, is the only prominent American locality.

### Göthite, $\text{Fe}(\text{OH})_3 \cdot \text{Fe}_2\text{O}_3$

**Form.** Göthite is found in small acicular crystals, in bladed crystal aggregates, and in scaly or fibrous masses. Crystals are orthorhombic, but are usually too minute to decipher.

**Cleavage,** in one direction parallel to the length.

**H.** =  $5\frac{1}{2}$ .

**Sp. gr.**  $\pm 4.3$ .

**Color**, yellowish-brown to nearly black. Streak, yellowish-brown like that of limonite. Luster.

**Optical Properties.**  $n > 1.93$ . Thin fragments are prismatic, and translucent brown with parallel extinction.

**Chemical Composition.** Iron hydroxid,  $\text{Fe}(\text{OH})_3 \cdot \text{Fe}_2\text{O}_3$  or  $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$ ; ( $\text{H}_2\text{O} = 10.1$  per cent.). Usually contains a little manganese.

**Blowpipe Tests.** Fusible with difficulty ( $5\frac{1}{2}$ ). In the closed tube turns red and gives off water. Iron bead tests.

Soluble in  $\text{HCl}$ .

**Uses.** As an ore of iron it is classed as brown hematite along with limonite.

**Occurrence.** 1. In iron-ore deposits along with limonite and hematite.

2. As inclusions in various minerals such as feldspars, quartz, etc.

### MANGANITE, $\text{Mn}(\text{OH})_3 \cdot \text{Mn}_2\text{O}_3$

**Form.** Manganite is found in prismatic crystals and in columnar and fibrous masses. Crystals are orthorhombic, prismatic in habit, and striated parallel to their length.

**Cleavage**, in one direction (010) parallel to the length of the crystal.

**H.** = 4.

**Sp. gr.**  $\pm 4.3$ .

**Color.** Iron-black or dark gray. Streak, dark brown. Luster, submetallic. Opaque.

**Chemical Composition.** Manganese hydroxid,  $\text{Mn}(\text{OH})_3 \cdot \text{Mn}_2\text{O}_3$  or  $\text{Mn}_2\text{O}_3 \cdot \text{H}_2\text{O}$ ; ( $\text{H}_2\text{O} = 10.3$  per cent.).

**Blowpipe Tests.** Infusible. In the closed tube gives water. Bead tests for manganese.

Soluble in  $\text{HCl}$  with the evolution of chlorin.

**Uses.** Manganite is an ore of manganese occurring along with pyrolusite and psilomelane.



**Occurrence.** 1. As a vein mineral. Ilfeld in the Hartz Mts. is a prominent locality.

2. As a secondary mineral in residual clays associated with psilomelane.

### LIMONITE, $2\text{Fe}(\text{OH})_3 \cdot \text{Fe}_2\text{O}_3$

**Form.** Limonite occurs in mammillary, botryoidal, and stalactitic forms and in fibrous, compact, pisolitic, nodular, porous, and earthy masses. It is never crystallized, but is often pseudomorphous after other iron minerals, especially pyrite.

**H.** =  $5\frac{1}{2}$ .

**Sp. gr.**  $\pm 3.8$ .

**Color,** yellow, brown, or black. **Streak,** yellowish-brown. **Luster,** submetallic to dull.

**Optical Properties.**  $n > 1.93$ . Fragments are either prismatic and acicular with parallel extinction or irregular and isotropic. They sometimes show a spherulitic cross.

**Chemical Composition.** Ferric hydroxid,  $2\text{Fe}(\text{OH})_3 \cdot \text{Fe}_2\text{O}_3$  or  $2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ ; (Fe = 59.8 per cent.;  $\text{H}_2\text{O}$  = 14.5 per cent.). Often impure from the presence of manganese oxid, phosphates, clay, sand, and organic matter.

**Blowpipe Tests.** Fusible with difficulty ( $5\frac{1}{2}$ ). When heated in R.F. becomes magnetic. In the closed tube turns red and gives water. Iron bead tests.

Soluble in HCl.

**Uses.** Limonite is a prominent ore of iron and in the United States ranks next to hematite in importance.

**Occurrence.** 1. As a secondary mineral in veins and ore-deposits formed by the oxidation of pyrite. Constitutes an important part of the gossan or "iron-hat."

2. As a metasomatic replacement of limestone.

3. As bog-iron ore formed by the oxidation of  $\text{FeH}_2(\text{CO}_3)_2$  which is in solution in marshes.

4. As a pigment and stain in various rocks.

**BAUXITE,  $\text{Al}_2\text{O}_3 \cdot x\text{H}_2\text{O}$** 

**Form.** Bauxite occurs in pisolitic forms, more rarely in clay-like masses, but never in crystals.

**H.** = 1 to 3.

**Sp. gr.**  $\pm 2.5$ .

**Color,** white, yellowish-white, pale red, or brownish-red. Luster, dull and earthy.

**Optical Properties.**  $n$  about 1.57. Fragments are irregular, isotropic in part, and have aggregate structure in part.

**Chemical Composition.** Bauxite is probably not a definite mineral, but a mixture of  $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$ ,  $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ , and iron hydroxids with hydrous aluminum silicate. The aluminum varies from 20 to 40 per cent. Some analyses correspond to  $\text{Al}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$  (Al = 39.1 per cent.). Bauxite usually contains both iron (up to 15 per cent.) and silica (up to 30 per cent.).

**Blowpipe Tests.** Infusible. Heated with cobalt nitrate solution it becomes blue. In the closed tube gives abundant water.

Soluble in HCl with difficulty.

**Uses.** Bauxite is now practically the only ore of aluminum. It is mined in Georgia, Alabama, and Arkansas.

**Occurrence.** (1) In beds formed by the decomposition of igneous rocks, in Arkansas from nepheline syenites.

2. In beds formed by thermal springs. The Georgia-Alabama deposits are accounted for in this manner.

**Brucite,  $\text{Mg}(\text{OH})_2$** 

**Form.** Brucite is occasionally found in crystals, but more often in foliated masses and sometimes in fibrous seams. Crystals are hexagonal and tabular in habit with the basal pinacoid and several rhombohedrons.

**Cleavage,** in one direction parallel to (0001).

**H.** =  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 2.4$ .

**Color,** white or greenish-white. Luster, pearly or silky.

**Optical Properties.**  $n_r(1.58) - n_a(1.56) = 0.02$ . Cleavage flakes

give a positive uniaxial interference figure without rings unless very thick. The fibrous variety gives acicular fragments with parallel extinction and negative elongation.

**Chemical Composition.** Magnesium hydroxid,  $\text{Mg}(\text{OH})_2$  or  $\text{MgO} \cdot \text{H}_2\text{O}$ ; ( $\text{H}_2\text{O} = 31.0$  per cent.). Often contains Fe and Mn. The manganese is due to the isomorphous replacement of  $\text{Mn}(\text{OH})_2$ .

**Blowpipe Tests.** Infusible, but glows. Heated with cobalt nitrate solution it turns pink. In the closed tube yields water and becomes opaque.

Soluble in HCl.

**Occurrence.** 1. As a secondary mineral in serpentine often associated with magnesite and dolomite. Texas, Pennsylvania, and Hoboken, New Jersey, are prominent localities.

### PSILOMELANE, $4\text{MnO}_2 \cdot (\text{Ba}, \text{K}_2)\text{O} \cdot \text{H}_2\text{O}?$

**Form.** Psilomelane is found in reniform, botryoidal, and mammillary forms. It is also compact massive and is one of the few minerals that never crystallizes.

**H.**  $= 5\frac{1}{2}$ .

**Sp. gr.**  $\pm 4.2$ .

**Color,** black. **Streak,** brownish-black. **Luster,** submetallic to dull. **Opaque.**

**Chemical Composition.** Impure hydrous manganese dioxid, perhaps  $4\text{MnO}_2 \cdot (\text{Ba}, \text{K}_2)\text{O} \cdot \text{H}_2\text{O}$ ; ( $\text{MnO}_2 = 70$  to  $90$  per cent;  $\text{H}_2\text{O} = 3$  to  $9$  per cent.). It usually contains barium and potassium and sometimes lithium.

**Blowpipe Tests.** Infusible. In the closed tube gives water and also oxygen. Manganese bead tests.

Soluble in HCl with the evolution of chlorin.

**Uses.** Psilomelane is an important ore of manganese and is also used as a source of chlorin.

**Occurrence.** 1. As a secondary mineral in residual clays. Batesville, Arkansas.

**WAD,  $\text{MnO}_2 + \text{H}_2\text{O}$  (impure)**

**Form.** Wad occurs in compact layers or in earthy, more or less porous, masses. It has never been found crystallized.

**H.** = 1 to 3.

**Sp. gr.** 3 to 4.5.

**Color,** brown to black. **Streak,** brown. **Luster,** dull.

**Chemical Composition.** Impure hydrous manganese dioxid; ( $\text{H}_2\text{O}$  = 10 to 20 per cent.). It usually contains Fe and may also contain Cu, Co, Li, or Ba.

**Blowpipe Tests.** Infusible. Gives water in the closed tube and also oxygen. Manganese bead tests.

Soluble in HCl with the evolution of chlorine.

**Uses.** Wad is used as a paint. Cobalt-bearing wad from New Caledonia is used as a source of cobalt.

**Occurrence.** (1) As a secondary mineral due to the weathering of other manganese minerals.

(2) In bog deposits, often associated with limonite.

## 8. CARBONATES

### A. Normal Anhydrous Carbonates

Calcite Group	CALCITE,	$\text{CaCO}_3$
	DOLOMITE,	$\text{CaMg}(\text{CO}_3)_2$
	Ankerite,	$\text{Ca}(\text{Mg,Fe})\text{CO}_3$
	MAGNESITE,	$\text{MgCO}_3$
	SIDERITE,	$\text{FeCO}_3$
	RHODOCHROSITE,	$\text{MnCO}_3$
Aragonite Group	SMITHSONITE,	$\text{ZnCO}_3$
	ARAGONITE,	$\text{CaCO}_3$
	Strontianite,	$\text{SrCO}_3$
	Witherite,	$\text{BaCO}_3$
	CERUSSITE,	$\text{PbCO}_3$

### B. Acid, Basic, and Hydrous Carbonates

MALACHITE	$\text{Cu}_2(\text{OH})_2\text{CO}_3$
AZURITE	$\text{Cu}_3(\text{OH})_2(\text{CO}_3)_2$
Hydrozincite	$\text{Zn}_3(\text{OH})_4\text{CO}_3$
Trona	$\text{Na}_3\text{H}(\text{CO}_3)_2 \cdot 2\text{H}_2\text{O}$
Hydromagnesite	$\text{Mg}_3(\text{OH})_2(\text{CO}_3)_3 \cdot 3\text{H}_2\text{O}$

The carbonates are not many in number, but they include some of the most common minerals with which the mineralogist has to deal. All the important normal carbonates fall into two well-defined isomorphous groups, the calcite group (rhombohedral) and the aragonite group (orthorhombic). These two groups are said to be isodimorphous, as calcite and aragonite are dimorphous.

### CALCITE GROUP—HEXAGONAL

The calcite group of rhombohedral carbonates is a well characterized group of familiar minerals. These minerals crystallize in rhombohedral and scalenohedral crystals with

cleavage parallel to the faces of a rhombohedron of about  $75^\circ$ . All except dolomite belong to the ditrigonal scalenohedral class of the hexagonal system. Dolomite belongs to the rhombohedral class, but is similar to the other minerals in angles and other properties. All the minerals of this group are uniaxial and optically negative and have very strong double refraction. Many isomorphous mixtures are known and some of them have special names (see mesitite below).

The following analyses are representative of the minerals mentioned and illustrate isomorphism. These analyses are recorded in the form of the metals and the carbonate radical,  $\text{CO}_3$ , instead of the usual method (oxids of the metals and  $\text{CO}_2$ ).

Analyses of Minerals of the Calcite Group

	Ca	Mg	Fe*	Mn	Zn	$\text{CO}_3$	Misc.
Calcite .....	40.0	.....	0.3	.....	.....	59.5	$\text{H}_2\text{O}=0.1$
Calcite .....	34.8	0.5	0.3	5.3	0.4	55.6	$\text{H}_2\text{O}=0.3$
Dolomite .....	21.7	12.0	1.3	.....	.....	64.8	Insol. = 0.2
Dolomite, (Brown-spar) .....	21.2	8.9	7.7	.....	.....	61.1	
Ankerite .....	20.3	6.1	13.4	.....	.....	60.3	
Magnesite .....	.....	29.2	.....	0.1	.....	69.6	$\text{H}_2\text{O}=1.4$
Magnesite (Breunnerite) .....	1.4	19.1	12.5	.....	.....	66.9	$\text{H}_2\text{O}=1.2$
Mesitite .....	0.1	16.3	20.7	.....	.....	62.9	
Siderite .....	0.1	.....	46.6	1.4	.....	51.8	
Siderite .....	0.4	1.9	36.7	8.2	.....	52.5	
Siderite, (Clay-ironstone) .....	0.1	.....	29.7	2.8	.....	35.1	*
Rhodochrosite .....	0.4	0.2	0.3	46.4	.....	52.0	
Smithsonite .....	0.3	.....	0.1	.....	51.3	47.3	†

\*  $\text{SiO}_2=12.3$ ,  $\text{Al}_2\text{O}_3=3.2$ ,  $\text{H}_2\text{O}=16.6$ .†  $\text{Cd}=0.7$ ,  $\text{S}=0.1$ ,  $\text{SiO}_2=0.1$ .

### CALCITE, $\text{CaCO}_3$

Calcite has played a very prominent part in the history of mineralogy. The discovery of cleavage in calcite led to the establishment of crystallography as an exact science by the Abbé Haüy, and the discovery of double refraction in calcite opened up the whole subject of crystal optics. The invention of

the Nicol prism, which is made of calcite, has made possible the identification of the fine-grained rocks.

**Form.** Calcite is found in well defined crystals, which are often large in size, in crystalline crusts and druses, in cleavable masses, in various imitative forms, such as stalactitic, pisolitic and oölitic, in granular masses, and sometimes in fibrous forms.

Calcite is the type example of the ditrigonal scalenohedral class of the hexagonal system. In number of forms and variety of their combinations, calcite is unsurpassed among minerals. Over 300 well established forms, most of them rhombohedrons and scalenohedrons, are known.  $c=0.854$ . Usual forms (in order

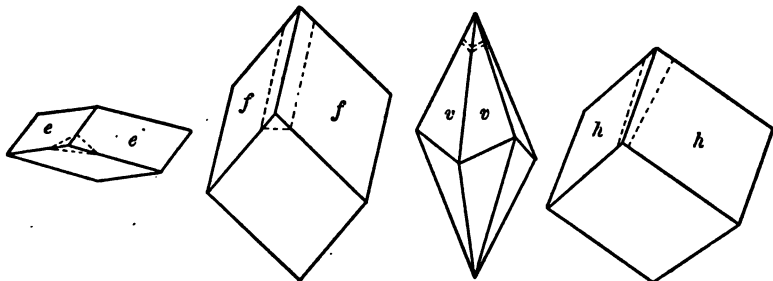


FIG. 461.

FIG. 462.

FIG. 463.

FIG. 464.

of their abundance):  $m\{10\bar{1}0\}$ ,  $c\{0001\}$ ,  $e\{01\bar{1}2\}$ ,  $f\{02\bar{2}1\}$ ,  $r\{10\bar{1}1\}$ ,  $M\{40\bar{4}1\}$ ,  $v\{21\bar{3}1\}$ ,  $a\{11\bar{2}0\}$ ,  $y\{32\bar{5}1\}$ ,  $t\{21\bar{3}4\}$ . Interfacial angles:  $ee(01\bar{1}2:\bar{1}012)=45^\circ 3'$ ;  $em\{01\bar{1}2:10\bar{1}0\}=63^\circ 45'$ ;  $rr(10\bar{1}1:\bar{1}101)=74^\circ 55'$ ;  $rm(10\bar{1}1:10\bar{1}0)=45^\circ 23\frac{1}{2}'$ ;  $ff(02\bar{2}1:\bar{2}021)=101^\circ 9'$ ;  $fm(02\bar{2}1:01\bar{1}0)=26^\circ 53'$ ;  $MM(40\bar{4}1:4401)=114^\circ 10'$ ;  $Mm(40\bar{4}1:10\bar{1}0)=14^\circ 13'$ ;  $vv(21\bar{3}1:\bar{2}3\bar{1}1)=75^\circ 22'$ ;  $vv(21\bar{3}1:3\bar{1}\bar{2}1)=35^\circ 36'$ ;  $vv(21\bar{3}1:12\bar{3}\bar{1})=47^\circ 1'$ ;  $rv(10\bar{1}1:21\bar{3}1)=29^\circ 1\frac{1}{2}'$ ;  $mv(10\bar{1}0:21\bar{3}1)=28^\circ 4'$ ;  $yy(32\bar{5}1:5\bar{2}3\bar{1})=45^\circ 32'$ ;  $yy(32\bar{5}1:\bar{3}5\bar{2}1)=70^\circ 59'$ ;  $tt(21\bar{3}4:\bar{2}3\bar{1}4)=41^\circ 55'$ ;  $tt(21\bar{3}4:3\bar{1}\bar{2}4)=20^\circ 36\frac{1}{2}'$ ;  $mm(10\bar{1}0:01\bar{1}0)=60^\circ 0'$ ;  $ma(10\bar{1}0:11\bar{2}0)=30^\circ 0'$ .

Figs. 461-480 represent typical calcite crystals. As can be seen, the habit is variable. Figs. 461-464 are simple forms. Fig. 461,  $e\{01\bar{1}2\}$ , is an obtuse rhombohedron while Fig. 462,

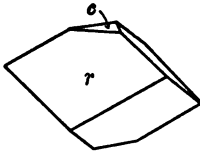


FIG. 465.

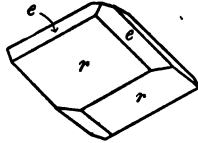


FIG. 466.

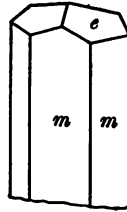


FIG. 467.

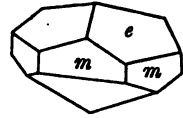


FIG. 468.

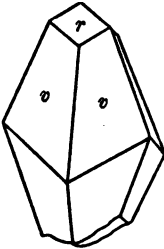


FIG. 469.

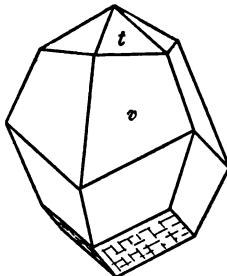


FIG. 470.



FIG. 471.

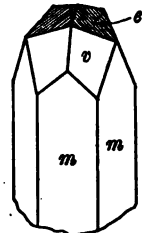


FIG. 472.

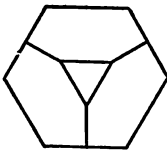


FIG. 473.

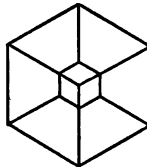


FIG. 474.

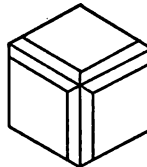


FIG. 475.

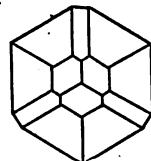


FIG. 476.

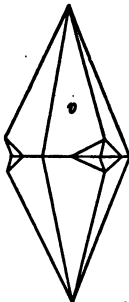


FIG. 477.

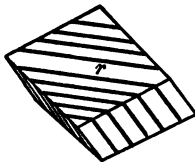


FIG. 478.

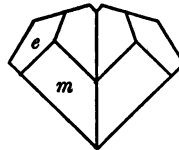


FIG. 479.

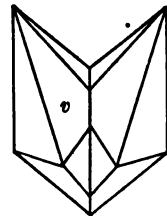


FIG. 480.

FIGS. 465-480.—Calcite Crystals.



amber colored calcite crystals occur in chert breccia in the zinc mines along underground water courses. Crystal Cave at Joplin is completely lined with calcite crystals from 1 to 2 feet in length. It is probable that the calcite was formed when the cave was completely filled with a water solution of calcium carbonate.

6. As the principal constituent of crystalline limestones, which were formed from sedimentary limestones by metamorphism. The crystalline limestones often contain diopside, tremolite, wollastonite, garnet, spinel, graphite, etc.

### DOLOMITE, $\text{CaMg}(\text{CO}_3)_2$

**Form.** Dolomite is found in crystals, in crystal druses, in cleavable masses, and in granular masses.

The crystals belong to the rhombohedral class of the hexagonal system and have a lower grade of symmetry than calcite crystals though this is not often apparent on inspection. The only common kind of dolomite crystals is the simple unit rhombohedron,

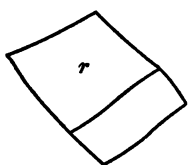


FIG. 482.

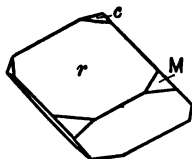


FIG. 483.

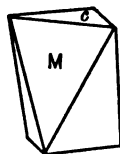


FIG. 484.

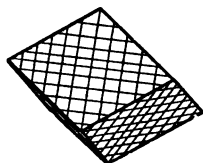


FIG. 485.

often curved and more or less saddle-shaped (Fig. 482). Fig. 483 is a rhombohedron modified by  $c\{0001\}$  and  $M\{40\bar{4}1\}$ . Crystals like Fig. 484 with  $c\{0001\}$  and  $M\{40\bar{4}1\}$  are found embedded in anhydrite and gypsum.

Several twinning laws are known for dolomite, but the only common one is polysynthetic twinning with  $\{02\bar{2}1\}$  as twin-plane which gives rise to striations on the cleavage faces parallel to both the short diagonal and the long diagonal of the rhomb (Fig. 485). This fact can often be used to distinguish dolomite from calcite.

**Cleavage,** rhombohedral like calcite.

**H.** =  $3\frac{1}{2}$  to 4.

**Sp. gr.** = 2.8

**Color**, white, pink or gray, but rarely colorless. Luster, pearly or vitreous. It is often called pearl spar.

**Optical Properties.**  $n_r(1.682) - n_a(1.503) = 0.179$ . Double refraction very strong. Fragments are rhombic with symmetrical extinction and very high order interference colors. The relief varies with the direction as in calcite. Gives the microchemical gypsum test with dilute  $H_2SO_4$ . In fragments it is distinguished from calcite by the absence of striations parallel to the long diagonal.

**Chemical Composition.** Calcium magnesium carbonate,  $CaMg(CO_3)_2$ ; (Ca = 21.6 per cent; Mg = 13.1 per cent.). It often contains iron and thus grades into ankerite. Analyses are given on page 333.

Dolomite is a double salt with equal molecular quantities of  $CaCO_3$  and  $MgCO_3$ , and not an isomorphous mixture of these two compounds.

**Blowpipe Tests.** Infusible and colors the flame yellowish red.

Large fragments are only slightly attacked by cold dilute  $HCl$ . Dolomite can thus be distinguished from calcite. In concentrated solutions  $H_2SO_4$  gives a white crystalline precipitate.

**Uses.** Dolomitic limestones, like ordinary limestones, are used for building and ornamental purposes and also for furnace linings.

**Occurrence.** 1. As a secondary mineral in cavities of limestones. The pink dolomite of the Joplin district is a prominent example of this occurrence.

2. As the essential constituent of dolomitic or magnesian limestones. These limestones are formed from ordinary limestones by the process known as dolomitization. This consists of the partial replacement of calcium carbonate by magnesium carbonate in a way not fully understood. As there is a shrinkage of about 10 per cent., these limestones are often porous.

3. As a vein mineral often associated with calcite as in the north of England.

4. As the principal constituent of the crystalline dolomitic limestones. These consist either of dolomite or of a mixture of dolomite and calcite. Other characteristic minerals are tremolite, phlogopite, chondrodite, olivine, spinel, serpentine, and talc. Serpentine and talc are secondary minerals formed from the other silicates.

### **Ankerite, $\text{Ca}(\text{Mg,Fe})(\text{CO}_3)_2$**

**Form.** Ankerite occurs in cleavable masses, rarely in small rhombohedral crystals resembling dolomite.

**Cleavage,** rhombohedral.

**H** =  $3\frac{1}{2}$  to 4.

**Sp. gr.**  $\pm 3.0$ .

**Color,** white to gray or brown.

**Optical Properties.** Similar to calcite and dolomite. Fragments are rhombic with symmetrical extinction and very high order interference colors. Gives the microchemical gypsum test with dilute  $\text{H}_2\text{SO}_4$ .

**Chemical Composition.** An isomorphous mixture of calcium, magnesium, and ferrous carbonates.  $\text{Ca}(\text{Mg,Fe})\text{CO}_3$ . It often contains manganese. Some analyses approximate  $2\text{CaCO}_3 \cdot \text{MgCO}_3 \cdot \text{FeCO}_3$ , which has been called normal ankerite.

**Blowpipe Tests.** Infusible. In the closed tube darkens. Becomes magnetic when heated on charcoal.

Soluble in hot  $\text{HCl}$  with effervescence.

**Occurrence.** 1. As a vein mineral, especially with the iron ores. Antwerp, New York.

### **MAGNESITE, $\text{MgCO}_3$**

**Form.** Magnesite occurs in cleavable or compact porcelain-like masses. It sometimes has a botryoidal surface, but is very rarely found in crystals.

**Cleavage.** Rhombohedral cleavage is sometimes prominent.

**Color,** white or gray. Luster, vitreous to dull.

H. = 4 to 5½.

Sp. gr.  $\pm 3.1$ .

**Optical Properties.**  $n_r(1.717) - n_a(1.515) = 0.202$ . Fragments are rhombic with symmetrical extinction or irregular with aggregate structure. The interference colors are very high order.

**Chemical Composition.** Magnesium carbonate,  $\text{MgCO}_3$ ; (Mg = 28.8 per cent.). Iron and calcium are often present. The massive varieties often contain magnesium silicate.

**Blowpipe Tests.** Infusible. Turns pink when heated with cobalt nitrate solution.

Soluble in hot HCl with effervescence.

**Uses.** Calcined magnesite is made into bricks for furnace lining. The carbon dioxide formed is liquefied and forms a valuable by-product. Magnesite is also used in paper-making and has other minor uses.

**Occurrence.** 1. In veins in serpentine (compact massive variety) resulting from the action of carbonated waters on olivine or on serpentine. Porterville, California and Red Mt. near Livermore, California.

2. In talc schists (cleavable variety) at several localities in the Alps.

### SIDERITE, $\text{FeCO}_3$

**Form.** Siderite is found in small crystals in cavities, in cleavable masses, in botryoidal crusts, and in compact masses.

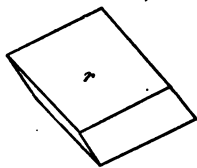


FIG. 486.

The crystals are varied in habit, the common forms being the unit rhombohedron ( $10\bar{1}1 : \bar{1}101 = 73^\circ 24'$ ), the rhombohedron  $\{01\bar{1}2\}$ , and the rhombohedron  $\{02\bar{2}1\}$ , the latter often modified by the pinacoid  $\{0001\}$ . Fig. 486 is the unit rhombohedron  $\{10\bar{1}1\}$ .

**Cleavage,** rhombohedral.

H. = 3½ to 4.

Sp. gr.  $\pm 3.8$ .

**Color,** various tints and shades of brown and gray.

**Optical Properties.**  $n_r(1.87) - n_a(1.63) = 0.24$ . Strong double refraction. Fragments are rhombic with symmetrical extinction.

tion and very high order interference colors. In methylene iodid the relief changes with the direction, but in both positions the index of refraction is greater than that of methylene iodid.

**Chemical Composition.** Ferrous carbonate,  $\text{FeCO}_3$ ; (Fe = 48.3 per cent.). Ca, Mg, and Mn are usually present in small amounts as replacing elements. Clay-ironstone is an impure massive siderite containing argillaceous material (see analysis, p. 333).

**Blowpipe Tests.** Fuses with difficulty. In the closed tube darkens. Heated on charcoal it becomes magnetic.

Soluble in hot HCl with effervescence. The solution gives tests for ferrous iron.

**Uses.** Siderite is one of the minor ores of iron. The clay-ironstone variety has been mined extensively in England and to some extent in Ohio, Pennsylvania, and Maryland.

**Occurrence.** 1. As a vein mineral.

2. As clay-ironstone concretions in shales.

3. As a secondary mineral in cavities of basalt. This variety is called sphaerosiderite as it is botryoidal.

### RHODOCHROSITE, $\text{MnCO}_3$

**Form.** Rhodochrosite occurs in rhombohedral crystals and in cleavable masses. The unit rhombohedron with  $(10\bar{1}1 : \bar{1}101) = 73^\circ 0'$  is the only common kind of crystal (Fig. 487).

**Cleavage,** rhombohedral.

**H.** = 4.

**Sp. gr.**  $\pm 3.5$ .

**Color,** pink, red or brownish-red.

**Optical Properties.**  $n_r(1.82) - n_a(1.60) = 0.22$ . Double refraction strong. Fragments are rhombic with symmetrical extinction and have very high order interference colors.

**Chemical Composition.** Manganous carbonate,  $\text{MnCO}_3$ ; (Mn = 47.8 per cent.). Calcium and iron are usually present.

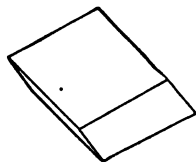


FIG. 487.

**Blowpipe Tests.** Infusible. In the closed tube it darkens and decrepitates. The borax bead in O.F. is amethyst color.

Soluble in warm HCl with effervescence.

**Uses.** Rhodochrosite is sometimes an ore of manganese.

**Occurrence.** 1. As a vein mineral. At Butte, Montana, it is the gangue of silver ores.

2. As a secondary mineral produced from rhodonite (Camp Bird Mine, Telluride, Colorado) and manganese phosphates (Branchville, Connecticut).

### SMITHSONITE, $\text{ZnCO}_3$

**Form.** Smithsonite usually occurs in mammillary or botryoidal incrusting forms and in porous masses. Crystals of smithsonite are comparatively rare and as a rule are much rounded.

**Cleavage,** imperfect rhombohedral and often curved.

**H.** = 5.

**Sp. gr.**  $\pm 4.4$ .

**Color,** white, gray, yellow; sometimes blue or green.

**Optical Properties.** Strong double refraction. Fragments are rhombic with symmetrical extinction and very high order interference colors. Index of refraction is greater than methylene iodid.

**Chemical Composition.** Zinc carbonate,  $\text{ZnCO}_3$ ; (Zn = 52.1 per cent.).

**Blowpipe Tests.** Infusible. Heated with cobalt nitrate solution on charcoal gives a green coating. In the closed tube turns yellow.

Soluble in HCl with effervescence.

**Uses.** Smithsonite is one of the ores of zinc and is often associated with calamine, the silicate. It is called "dry-bone" in the Wisconsin-Illinois-Iowa zinc district.

**Occurrence.** 1. As a secondary mineral formed from sphalerite. It also occurs as a metasomatic replacement of limestone,

and is often pseudomorphous after calcite and dolomite. Marion County, Arkansas, is a prominent locality.

### ARAGONITE GROUP—ORTHORHOMBIC

The aragonite group is another isomorphous group, though not so well defined as the calcite group. The crystals are orthorhombic, but pseudohexagonal ( $110:\bar{1}\bar{1}0=62^\circ-64^\circ$ ) and are usually prismatic in habit. Twinning on the unit prism  $\{110\}$  is very common and also accounts for the pseudohexagonal character of some crystals. Optically the minerals are biaxial with a small axial angle. The double refraction is very strong as in the calcite group.

### ARAGONITE, $\text{CaCO}_3$

**Form.** Aragonite occurs in crystals, in columnar and fibrous masses and in incrusting and stalactitic forms. Fibrous masses are especially common for aragonite, but rare for calcite.

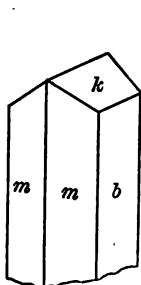


FIG. 488.

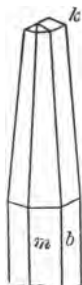


FIG. 489.

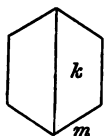


FIG. 490.

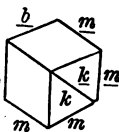


FIG. 491.

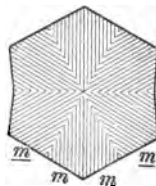


FIG. 492.

The crystals are usually prismatic or acicular in habit, and belong to the bipyramidal class of the orthorhombic system. Usual forms:  $m\{110\}$ ,  $b\{010\}$ ,  $k\{011\}$ . Interfacial angles:  $mm(110:\bar{1}\bar{1}0)=63^\circ 48'$ ;  $mb(110:010)=58^\circ 6'$ ;  $bk(010:011)=$

54° 13½'. Figs. 488 and 489 are drawings of typical crystals. The pseudo-hexagonal character can be seen from Fig. 490. Twins with  $m\{110\}$  as twin-plane are common. Fig. 491 is a contact twin and Fig. 492, a penetration twinning with slight reëntrant angles.

**Cleavage**, imperfect parallel to the length of the crystals (010 face). Calcite has cleavage oblique to the length of the crystals.

**H.** = 3½.

**Sp. gr.** ± 2.9.

**Color**, colorless, white or amber. Luster, vitreous, faint resinous on fracture.

**Optical Properties.**  $n_r = (1.68) - n_a(1.53) = 0.15$ . Double refraction very strong. Fragments are prismatic with parallel extinction, negative elongation, and very high order interference colors. Gives the microchemical gypsum test with dilute  $H_2SO_4$ .

**Chemical Composition.** Calcium carbonate,  $CaCO_3$ ; (Ca = 40.0 per cent.). It often contains a small amount of  $SrCO_3$ .

**Blowpipe Tests.** Infusible, but becomes opaque and falls to pieces when heated.

Soluble in cold dilute acids with effervescence. In a concentrated solution dilute  $H_2SO_4$  gives a crystalline precipitate of  $CaSO_4 \cdot 2H_2O$ . Finely powdered aragonite (also strontianite and witherite) heated in a test-tube with cobalt nitrate solution becomes lilac colored, while calcite is practically unchanged.

**Occurrence.** 1. As a secondary mineral in basic igneous rocks such as basalt.

2. As a secondary mineral in seams and cavities of limestones along with calcite.

3. In clays and marls along with gypsum. Prominent localities are Girgenti in Sicily and the Pyrenees.

4. As a hot-spring deposit. Carlsbad, Bohemia. Aragonite forms above 30° C. as a crust in a tea-kettle.

5. As the mother-of-pearl layer of mollusc shells.

6. As a secondary mineral in serpentine, produced by the decomposition of the pyroxene of the original peridotite.



**Strontianite,  $\text{SrCO}_3$** 

**Form.** Strontianite occurs in acicular crystals and also in columnar and fibrous masses. The crystals are pseudohexagonal orthorhombic and resemble those of aragonite.

**H.** =  $3\frac{1}{2}$  to 4.

**Sp. gr.**  $\pm 3.7$ .

**Color,** colorless, white or pale colors.

**Optical Properties.**  $n_\gamma(1.67) - n_\alpha(1.52) = 0.15$ . Like those of aragonite, but gives faint test, if any, for microchemical gypsum.

**Chemical Composition.** Strontium carbonate,  $\text{SrCO}_3$ ; (Sr = 59.3 per cent.). Usually contains some  $\text{CaCO}_3$ , which may be detected by the microchemical gypsum test.

**Blowpipe Tests.** Infusible but swells up and gives a crimson flame when heated after moistening with HCl.

Soluble in HCl with effervescence. In dilute solutions,  $\text{H}_2\text{SO}_4$  gives a finely divided white precipitate which distinguishes strontianite from aragonite.

**Uses.** The strontium hydroxid used in sugar refining is made from strontianite.

**Occurrence.** 1. As a secondary mineral in veins along with celestite and barite.

2. In veins in calcareous marl. Hamm in Westphalia, Germany, is a prominent locality.

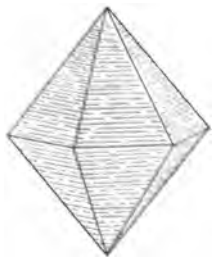


Fig. 493.

**Witherite,  $\text{BaCO}_3$** 

**Form.** Witherite occurs in granular or columnar masses in crystalline druses, and in distinct crystals. The crystals are pseudohexagonal twins of pyramidal habit often resembling quartz crystals. (See Fig. 493.)

**H.** =  $3\frac{1}{2}$ .

**Sp. gr.**  $\pm 4.3$ .

**Color,** white or gray. Luster, faint resinous or vitreous.

**Optical Properties.**  $n_\gamma(1.67) - n_\alpha(1.52) = 0.15$ . The optical properties are like those of aragonite.

**Chemical Composition.** Barium carbonate,  $\text{BaCO}_3$ ; ( $\text{Ba}=69.6$  per cent.).

**Blowpipe Tests.** Easily fusible giving a yellowish-green flame. Soluble in  $\text{HCl}$  with effervescence. In dilute solution  $\text{H}_2\text{SO}_4$  gives a finely divided white precipitate.

**Occurrence.** 1. In veins with galena. Barite is a secondary mineral. The North of England is the only prominent locality for witherite.

### CERUSSITE, $\text{PbCO}_3$

**Form.** Cerussite occurs in fibrous and reticulated forms, in compact masses, and often in crystals which are orthorhombic and pseudo-hexagonal. The habit is usually parallel to the side pinacoid  $b\{010\}$  (Fig. 495) or pyramidal with  $p\{111\}$  and  $i\{021\}$  in about equal development (Fig. 494). In these figures  $m\{110\}$ ,  $a\{100\}$ ,  $r\{130\}$ ,  $k\{011\}$ .

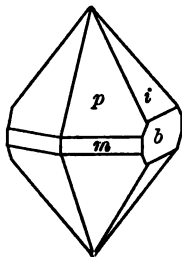


FIG. 494.

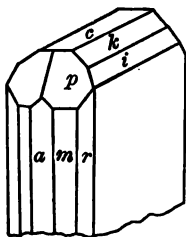


FIG. 495.

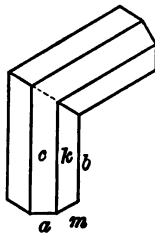


FIG. 496.

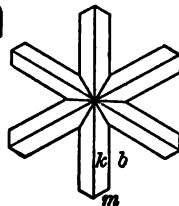


FIG. 497.

Twinning ( $m\{110\}$  as twin-plane) is common both as simple contact twins like Fig. 496 and as interpenetrant twins like Fig. 497.

**H.**  $=3\frac{1}{2}$ .

**Sp. gr.**  $\pm 6.5$ .

**Color,** colorless, white, gray, and other pale colors. **Luster,** adamantine.

**Optical Properties.**  $n_r(2.07) - n_a(1.80) = 0.27$ . Double refraction very strong. Fragments are mostly irregular with very high

order interference colors and index of refraction greater than methylene iodid. With  $\text{HNO}_3$ , octahedral crystals of lead nitrate form.

**Chemical Composition.** Lead carbonate,  $\text{PbCO}_3$ ; ( $\text{Pb}=77.5$  per cent.).

**Blowpipe Tests.** Fuses easily. In the closed tube decrepitates and becomes yellow. Heated on charcoal in R.F. it gives a metallic button and a yellow coating.

Soluble in  $\text{HNO}_3$  with effervescence. Soluble in hot  $\text{HCl}$ , but on cooling needle crystals of adamantine luster ( $\text{PbCl}_2$ ) separate out.

**Uses.** Cerussite is an ore of lead and sometimes is argentiferous.

**Occurrence.** 1. As a secondary mineral derived from galena. It occurs especially in the gossan of ore-deposits. Prominent localities are Broken Hill, New South Wales, and Coeur d'Alene district, Idaho. In the Joplin district cerussite pseudomorphs after galena are found.

### MALACHITE, $\text{Cu}_2(\text{OH})_2\text{CO}_3$

**Form.** For malachite the characteristic occurrences are mammillary crusts, fibrous masses, and acicular crystals. The crystals are monoclinic, but are usually very small and indistinct.

**H.**  $=3\frac{1}{2}$  to 4.

**Sp. gr.**  $\pm 3.9$ .

**Color,** emerald green.

**Optical Properties.**  $n_p=1.88$ . Fragments are prismatic with oblique extinction ( $23^\circ$ ). Interference colors are masked by the green color of the mineral. Arrowhead twins like gypsum are common among the fragments.

**Chemical Composition.** Basic copper carbonate,  $\text{Cu}_2(\text{OH})_2\text{CO}_3$ , or  $\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$ ; ( $\text{Cu}=57.4$  per cent.;  $\text{H}_2\text{O}=8.1$  per cent.).

**Blowpipe Tests.** Easily fusible (3) giving a green flame which is made blue by  $\text{HCl}$ . In the closed tube it turns black and gives off  $\text{H}_2\text{O}$ .

Soluble in acids with effervescence.

**Uses.** Malachite is sometimes an ore of copper, together with azurite, cuprite, and chrysocolla which are collectively called oxidized ores. Polished malachite with a concentric fibrous structure is used as an ornamental stone.

**Occurrence.** 1. As a secondary mineral in the upper oxidized zone of copper deposits. It constitutes the so-called "copper-stain." Malachite is often associated with azurite and is sometimes pseudomorphous after it. Bisbee, Arizona, is a prominent locality.

### AZURITE, $\text{Cu}_3(\text{OH})_4(\text{CO}_3)_2$

**Form.** Azurite occurs in crystals in crystalline coatings and nodular groups of crystals. Crystals are monoclinic, prismatic class, and are usually short prismatic or tabular in habit, often highly modified. The best specimens come from Chessy in France, hence chessylite, the French name for azurite.

**H.** = 4.

**Sp. gr.**  $\pm 3.8$ .

**Color,** deep azure blue.

**Optical Properties.**  $n > 1.83$ . Fragments are irregular, blue in color, but not pleochroic. Interference colors are masked.

**Chemical Composition.** Basic copper carbonate,  $\text{Cu}_3(\text{OH})_4(\text{CO}_3)_2$  or  $2\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$ ; (Cu = 55.2 per cent.,  $\text{H}_2\text{O}$  = 5.2 per cent.).

**Blowpipe Tests.** The same as for malachite.

**Uses.** Azurite is one of the so-called oxidized copper ores.

**Occurrence.** 1. As a secondary mineral in the oxidized zone. It is usually associated with malachite and has been formed after the malachite. Bisbee, Arizona, is a prominent locality.

### Hydrozincite, $\text{Zn}_5(\text{OH})_4\text{CO}_3$

**Form.** The characteristic occurrence of hydrozincite is in concentric crusts. It also occurs in stalactites and in earthy masses but has never been found in crystals.

**H.** =  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 3.7$ .

**Color,** white. **Luster,** dull.

**Optical Properties.**  $n > 1.74$ . Fragments show aggregate structure (often banded) and give bright interference colors.

**Chemical Composition.** Basic zinc carbonate,  $\text{Zn}_3(\text{OH})_4\text{CO}_3$  or  $\text{ZnCO}_3 \cdot 2\text{Zn}(\text{OH})_2$ ; (Zn = 60.8 per cent.;  $\text{H}_2\text{O}$  = 11.1 per cent.)

**Blowpipe Tests.** Infusible. In the closed tube gives off water and turns yellow. On charcoal with cobalt nitrate solution it turns bright green.

Soluble in HCl with effervescence.

**Occurrence.** 1. As a secondary mineral resulting from the decomposition of other zinc minerals. Often occurs in layers with smithsonite or calamine. Santander, Spain is a prominent locality.

### Trona, $\text{Na}_3\text{H}(\text{CO}_3)_2 \cdot 2\text{H}_2\text{O}$

**Form.** Trona occurs in crystals and crystalline crusts. The crystals are monoclinic and tabular in habit.

**H.** =  $2\frac{1}{2}$  to 3.

**Sp. gr.**  $\pm 2.1$ .

**Color,** white or colorless.

**Optical Properties.**  $n_p = 1.51$ . Recrystallizes from water solution in rosettes. (Fig. 498.)

**Chemical Composition.** Hydrrous sodium acid carbonate,  $\text{Na}_3\text{H}(\text{CO}_3)_2 \cdot 2\text{H}_2\text{O}$  or  $\text{NaCO}_3 \cdot \text{NaHCO}_3 \cdot 2\text{H}_2\text{O}$ ; ( $\text{H}_2\text{O}$  = 19.9 per cent.).

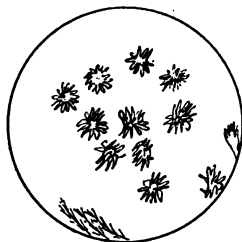


FIG. 498.  
Trona recrystallized.

**Blowpipe Tests.** Easily fusible ( $1\frac{1}{2}$ ) giving an intense yellow flame. On gentle heating in the closed tube gives off water, but does not melt.

Soluble in water. Effervesces with HCl.

**Occurrence.** 1. Trona is formed by the evaporation of the water in soda lakes. Owens Lake, Inyo County, California, is a prominent locality.

### Hydromagnesite, $\text{Mg}_4(\text{OH})_2(\text{CO}_3)_3 \cdot 3\text{H}_2\text{O}$

**Form.** Hydromagnesite occurs in crystalline crusts, thin seams, and earthy chalk-like masses. Crystals, which are very small, are usually like Fig. 499, and are either orthorhombic or monoclinic with  $\beta = 90^\circ$ .

**H.** = 1 to 3.

**Sp. gr.**  $\pm 2.1$ .

**Color,** white. **Luster,** often pearly.

**Optical Properties.**  $n_g = 1.53$ . Fragments and crystals are prismatic with parallel extinction, negative elongation, and low-order interference colors.

**Chemical Composition.** Hydrous basic magnesium carbonate,  $\text{Mg}_4(\text{OH})_2(\text{CO}_3)_3 \cdot 3\text{H}_2\text{O}$  or  $3\text{MgCO}_3 \cdot \text{Mg}(\text{OH})_2 \cdot 3\text{H}_2\text{O}$ ; ( $\text{H}_2\text{O} = 19.8$  per cent.).

**Blowpipe Tests.** Infusible. In the closed tube gives off water.

Soluble in HCl with effervescence.

**Occurrence.** 1. As a secondary mineral in serpentine often with brucite as an associate. Alameda County, California.

2. As the product of the dedolomitization (see glossary) of magnesian limestone. Predazzite from Tyrol is a metamorphic limestone consisting of calcite and hydromagnesite.

A large deposit of hydromagnesite occurs at Atlin, British Columbia. This deposit is at least five feet thick and is probably a spring deposit.

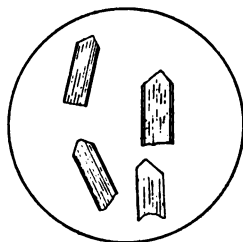


FIG. 499.

## 9. PHOSPHATES, ARSENATES, ETC.

### A. Normal Anhydrous Phosphates, etc.

	Columbite,	$(\text{Fe}, \text{Mn})(\text{Nb}, \text{Ta})_2\text{O}_6$
	Monazite,	$(\text{Ce}, \text{La})\text{PO}_4$
	Triphylite,	$\text{Li}(\text{Fe}, \text{Mn})\text{PO}_4$
Apatite Group	APATITE,	$\text{Ca}_{10}(\text{F}, \text{Cl}, \text{O}, \text{CO}_3)(\text{PO}_4)_6$
	Pyromorphite,	$\text{Pb}_3\text{Cl}(\text{PO}_4)_3$
	Mimetite,	$\text{Pb}_3\text{Cl}(\text{AsO}_4)_3$
	Vanadinite,	$\text{Pb}_3\text{Cl}(\text{VO}_4)_3$

### B. Acid, Basic, and Hydrous Phosphates

	Amblygonite,	$\text{LiAl}(\text{F}, \text{OH})\text{PO}_4$
	Olivenite,	$\text{Cu}_2(\text{OH})\text{AsO}_4$
Vivianite Group	Vivianite,	$\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$
	Erythrite,	$\text{Co}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$
	Wavellite,	$\text{Al}_3(\text{OH})_3(\text{PO}_4)_3 \cdot 5\text{H}_2\text{O}$
	Turquois,	$\text{H}_6[\text{Al}(\text{OH})_2]_6\text{Cu}(\text{OH})(\text{PO}_4)_4$

With the phosphates are included also the analogous compounds, arsenates and vanadates. Columbite properly belongs to another division, the niobates and tantalates, but is placed here for convenience.

About 150 phosphate minerals are known but most of them are rare. Basic phosphates of iron and of copper are especially numerous. The compounds are practically all orthophosphates, that is, salts of  $\text{H}_3\text{PO}_4$ .

#### Columbite, $(\text{Fe}, \text{Mn})(\text{Nb}, \text{Ta})_2\text{O}_6$

**Form.** Columbite usually occurs in orthorhombic crystals of short prismatic or tabular habit.

**Cleavage,** fair in two directions at right angles.

**H.** = 6.

**Sp. gr.** 5.5 to 6.5.

**Color**, black, often iridescent. **Luster**, submetallic.

**Chemical Composition.** An iron-manganese meta-niobate and meta-tantalate grading from  $(\text{Fe,Mn})\text{Nb}_2\text{O}_6$  to  $(\text{Fe,Mn})\text{Ta}_2\text{O}_6$ . The latter mineral is called tantalite.

**Blowpipe Tests.** Fusible on the edges with difficulty ( $5\frac{1}{2}$ ). On charcoal with soda in R.F. gives a magnetic residue. The soda bead in O.F. is bluish-green (Mn.). The borax fusion dissolved in HCl with tin gives a deep blue color.

Insoluble in acids.

**Uses.** Tantalum, which is used as a filament for incandescent lights, is obtained from columbite and tantalite.

**Occurrence.** 1. In granite-pegmatites, associated with beryl, lepidolite, spodumene, etc. The Etta mine in the Black Hills, South Dakota, is the most prominent locality in the United States.

### Monazite, $(\text{Ce,L a})\text{PO}_4$

**Form.** Monazite is usually found in the form of sand and occasionally in small embedded crystals. The crystals are monoclinic, but are difficult to decipher on account of their small size.

**Cleavage**, usually perfect in one direction.

**H.** = 5.

**Sp. gr.**  $\pm 5.1$ .

**Color**, yellow to yellowish-brown or reddish-brown. **Luster**, faint resinous.

**Optical Properties.**  $n_p = 1.79$ . Double refraction, strong. Fragments are plates, pale yellow in color, and with rather high interference colors (3rd to 5th order).

**Chemical Composition.** Cerium-lanthanum phosphate. Silica and the rare metals, Th, Pr, Nd, and Y are usually present.

**Blowpipe Tests.** Infusible, but turns gray on heating. The flame coloration with  $\text{H}_2\text{SO}_4$  is pale bluish-green.

Decomposed by acids. To get the phosphate test make a soda fusion.

**Uses.** Welsbach gas mantles are prepared from the thorium,



$\text{ThO}_2$ , obtained from monazite. The principal commercial deposit is near Prado, Bahia, Brazil.

**Occurrence.** 1. In gneisses and granites as an accessory constituent. Derby has proved its wide distribution in decomposed gneisses of Brazil.

2. In sands along with other heavy minerals. Occurs in western North Carolina and in the beach sands of Brazil.

### Triphylite, $\text{Li(Fe,Mn)PO}_4$

**Form.** The characteristic occurrence of triphylite is in cleavable masses. Crystals are rare.

**Cleavage,** perfect in one direction.

**H.** =  $4\frac{1}{2}$  to 5.

**Sp. gr.**  $\pm 3.5$ .

**Color,** usually bluish-gray.

**Optical Properties.**  $n = 1.69$ . Double refraction weak. Fragments are plates with low-order interference colors.

**Chemical Composition.** Lithium iron-manganese phosphate,  $\text{Li(Fe,Mn)PO}_4$ , the two compounds  $\text{LiFePO}_4$  and  $\text{LiMnPO}_4$  being isomorphous.

**Blowpipe Tests.** Easily fusible ( $2\frac{1}{2}$ ) to a magnetic globule, coloring the flame purplish-red.

Soluble in HCl.

**Occurrence.** 1. In granite-pegmatites. Branchville, Connecticut, is a prominent locality. A large number of other manganese-iron phosphates from this locality were described by Brush and Dana.

### APATITE GROUP—HEXAGONAL

The apatite group is a well-established isomorphous group of minerals, for several isomorphous mixtures are known as given in the analyses below. Besides fluor-apatite  $3\text{Ca}_3(\text{PO}_4)_2 \cdot \text{CaF}_2$  and chlor-apatite,  $3\text{Ca}_3(\text{PO}_4)_2 \cdot \text{CaCl}_2$ , there is dahllite,  $3\text{Ca}_3(\text{PO}_4)_2 \cdot \text{CaCO}_3$ , voelckerite,  $3\text{Ca}_3(\text{PO}_4)_2 \cdot \text{CaO}$ , and a rare mineral called

svabite,  $3\text{Ca}(\text{AsO}_4)_2 \cdot \text{CaF}_2$ . The following are typical analyses of the minerals of this group:

Analyses of Minerals of the Apatite Group

	Ca	Pb	$\text{PO}_4$	$\text{AsO}_4$	$\text{VO}_4$	Cl	F	Misc.
Fluor-apatite, Portland .....	39.5	.....	55.4	.....	.....	0.2	3.8	1.1
Chlor-apatite, Norway .....	37.2	.....	54.2	.....	.....	5.0	.....	3.1
Dahlite (Podolite), Russia .....	36.5	.....	52.2	.....	.....	.....	.....	$\text{CO}_2 = 5.3, *$
Voelckerite, Zillerthal .....	40.4	.....	57.5	.....	.....	.....	0.6	$\text{O} = 1.4, \dagger$
Polysphaerite, Freiberg .....	4.6	67.0	26.0	0.8	.....	1.9	.....	.....
Pyromorphite, Schemnitz .....	0.2	75.1	21.3	.....	.....	2.5	.....	.....
Pyromorphite, Roughten Gill .....	.....	71.7	15.1	10.9	.....	2.3	.....	1.7
Mimetite, Bohemia .....	.....	70.6	0.8	26.7	.....	2.5	.....	.....
Endlichite, New Mexico .....	0.2	68.2	tr	16.1	13.7	2.5	.....	.....
Vanadinite, Arizona .....	.....	71.7	1.9	.....	24.7	2.4	.....	.....
Svabite, Jakobsberg .....	30.1	2.8	0.5	61.7	.....	0.1	2.0	2.6

\*  $\text{Fe}_2\text{O}_3 = 3.0$  $\dagger \text{H}_2\text{O} = 0.1$ 

### APATITE, $\text{Ca}_{10}(\text{F}_2, \text{Cl}_2, \text{O}, \text{CO}_3)(\text{PO}_4)_6$

**Form.** Apatite is found in crystals, in massive forms, and in concretions. The crystals are hexagonal and belong to the bipyramidal class as there is but one plane of symmetry, which is horizontal. The habit is usually prismatic with the following forms:  $m\{10\bar{1}0\}$ ,  $c\{0001\}$ , and  $p\{10\bar{1}1\}$ . Interfacial angles:  $m\bar{p}(10\bar{1}0:10\bar{1}1) = 49^\circ 42'$ ;  $\bar{p}\bar{p}(10\bar{1}1:01\bar{1}1) = 37^\circ 44\frac{1}{2}'$ . Figs. 500 to 503 represent usual types of crystals. In Fig. 502, the general form  $\mu\{21\bar{3}1\}$  is present in addition to  $s\{11\bar{2}1\}$  and other forms.

**Cleavage,** imperfect basal parallel to  $\{0001\}$ .

**H.** = 5.

**Sp. gr.**  $\pm 3.2$ .

**Color,** usually reddish-brown or green, more rarely white, colorless, or violet.

**Optical Properties.**  $n_r(1.646) - n_a(1.641) = 0.005$ . Fragments are irregular, and colorless with low first order interference colors. Gives the microchemical gypsum test with  $\text{H}_2\text{SO}_4$ .

**Chemical Composition.** Apatite is an isomorphous mixture of

$\text{Ca}_{10}\text{F}_2(\text{PO}_4)_6$  with  $\text{Ca}_{10}\text{Cl}_2(\text{PO}_4)_6$ ,  $\text{Ca}_{10}\text{O}(\text{PO}_4)_6$ , and  $\text{Ca}_{10}(\text{CO}_3)(\text{PO}_4)_6$ . For  $\text{Ca}_{10}\text{F}_2(\text{PO}_4)_6$ , Ca=39.7 per cent., F=3.8 per cent.,  $\text{PO}_4=56.5$  per cent.

**Blowpipe Tests.** Fusible on edges (5½), giving a yellowish-red flame.

Soluble in  $\text{HNO}_3$ , sometimes with slight effervescence on heating. The solution gives a yellow precipitate with  $(\text{NH}_4)_2\text{MoO}_4$  on warming. The best test for calcium is dilute  $\text{H}_2\text{SO}_4$ , which gives needle crystals of  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ .  $\text{NH}_4\text{OH}$  gives a white precipitate of calcium phosphate.

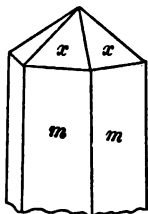


FIG. 500.

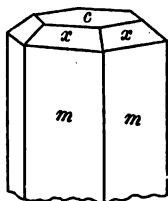


FIG. 501.

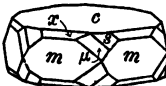


FIG. 502.

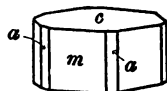


FIG. 503.

**Uses.** Massive apatite and phosphate rock are used extensively as a source of phosphates for fertilizers.

**Occurrence.** 1. As an accessory constituent of igneous rocks, very common and widely distributed but in small quantities.

2. In veins in gabbro associated with wernerite and rutile. The chlor-apatite of Norway Vogt believes to have been formed by a pneumatolytic process.

3. In clefts of gneisses and schists. St. Gothard, Switzerland, furnishes good specimens.

4. In pegmatites and tin-stone veins.

5. As a metasomatic replacement of limestone. Some massive apatites or phosphorites have been formed in this way.

### Phosphate Rock, etc.

Phosphate rock is an impure massive calcium phosphate near apatite in composition. It occurs in beds, either in irregular

concretionary masses or in nodules. Besides calcium phosphate, it contains organic matter, varying amounts of iron and aluminum, and calcium carbonate. The calcium carbonate is present partly as calcite, but principally as the dahllite molecule,  $3\text{Ca}_3(\text{PO}_4)_2 \cdot \text{CaCO}_3$ .

Phosphate rock is used extensively as a source of superphosphate for fertilizers. The crude minerals are treated with  $\text{H}_2\text{SO}_4$ . Florida, South Carolina, and Tennessee have important deposits. Large deposits have recently been discovered in Idaho, Wyoming, and Utah.

### Pyromorphite, $\text{Pb}_5\text{Cl}(\text{PO}_4)_3$

**Form.** Pyromorphite usually occurs as small crystals and earthy crusts. The crystals are hexagonal and prismatic in habit,  $c\{0001\}$  and  $m\{10\bar{1}0\}$  being the only common forms (Fig. 504).

**H.** =  $3\frac{1}{2}$  to 4.

**Sp. gr.**  $\pm 6.8$ .

**Color,** green or brown. **Luster,** adamantine.

**Optical Properties.**  $n_r(2.061) - n_a(2.049) = 0.012$ . Fragments are irregular, colorless or pale green, and have low first-order interference colors. With  $\text{HNO}_3$  isometric crystals are deposited.

**Chemical Composition.** Lead chlorid-phosphate,  $\text{Pb}_5\text{Cl}(\text{PO}_4)_3$ ; (Pb = 76.3 per cent.). In some varieties Ca replaces Pb (polysphaerite, p. 355) and in others ( $\text{VO}_4$ ) replaces ( $\text{PO}_4$ ).

**Blowpipe Tests.** Easily fusible (2) on charcoal to a globule with apparent crystal faces. With soda on charcoal yields a lead button. With a  $\text{NaPO}_3$  bead saturated with  $\text{CuO}$  it gives an azure-blue flame (Cl).

Soluble in  $\text{HNO}_3$ .  $(\text{NH}_4)_2\text{MoO}_4$  gives a yellow precipitate with the nitric acid solution.

**Occurrence.** 1. As a secondary mineral formed from galena. Phoenixville, Pennsylvania, is a prominent locality. Both pyro-

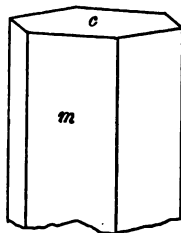


FIG. 504.

morphite pseudomorphs after galena and galena pseudomorphs after pyromorphite have been noted, the former from the Joplin district and the latter from Huelgoat, France.

### Mimetite, $\text{Pb}_3\text{Cl}(\text{AsO}_4)_3$

**Form.** Mimetite usually occurs in rounded hexagonal crystals.

**H.** =  $3\frac{1}{2}$ .

**Sp. gr.**  $\pm 7.2$ .

**Color,** yellow, orange, or red. **Luster** adamantine.

**Optical Properties.**  $n_\gamma(2.13) - n_\alpha(2.12) = 0.01$ . Fragments are irregular, yellow and have low first-order interference colors. With  $\text{HNO}_3$  isometric crystals of  $\text{Pb}(\text{NO}_3)_2$  are deposited.

**Chemical Composition.** Lead chlorid-arsenate,  $\text{Pb}_3\text{Cl}(\text{AsO}_4)_3$ ; ( $\text{Pb} = 69.5$  per cent.). It grades on the one hand into pyromorphite and on the other into vanadinite.

**Blowpipe Tests.** Easily fusible ( $1\frac{1}{2}$ ) on charcoal and gives a white sublimate and a metallic button. In the closed tube heated with charcoal it gives an arsenic mirror. With  $\text{CuO}$  in the  $\text{NaPO}_3$  bead it gives an azure-blue flame ( $\text{Cl}$ ).

Soluble in  $\text{HNO}_3$ . With  $(\text{NH}_4)_2\text{MoO}_4$  the nitric acid solution gives a yellow precipitate on boiling (phosphates give the precipitate on slight warming).

**Occurrence.** 1. As a secondary mineral in lead mines. Cumberland, England.

### Vanadinite, $\text{Pb}_3\text{Cl}(\text{VO}_4)_3$

**Form.** Vanadinite practically always occurs in small hexagonal crystals of prismatic habit. The common forms are:  $c\{0001\}$  and  $m\{10\bar{1}0\}$  (Fig. 505). The general form  $\{21\bar{3}1\}$ , a hexagonal bipyramid, is sometimes present.

**H.** = 3.

**Sp. gr.**  $\pm 6.8$ .

**Color,** usually red, but also yellow and brown. **Luster,** adamantine.

**Optical Properties.**  $n_\gamma(2.35) - n_\alpha(2.30) = 0.05$ . Fragments are

irregular yellow or orange color, and give bright interference colors.

**Chemical Composition.** Lead chlorid-vanadate,  $\text{Pb}_5\text{Cl}(\text{VO}_4)_3$ ; ( $\text{Pb}=72.7$  per cent.). It often contains  $(\text{PO}_4)$  and  $(\text{AsO}_4)$  as replacing radicals. Endlichite is between vanadinite and mimetite (see analyses, page 355).

**Blowpipe Tests.** Easily fusible ( $1\frac{1}{2}$ ) on charcoal giving a white sublimate and a metallic globule. In the closed tube with  $\text{KHSO}_4$  gives a yellow mass. The  $\text{NaPO}_3$  bead is green in R.F. and yellow in O.F. It gives the Cl test with  $\text{NaPO}_3$  bead and  $\text{CuO}$ .

Soluble in  $\text{HNO}_3$ .

**Uses.** Vanadinite is one source of the vanadium used as an alloy with steel, and of various compounds used in dyeing and in the manufacture of ink.

**Occurrence.** 1. A secondary mineral formed from galena. Yuma County, Arizona, is a prominent locality. Vanadinite often occurs with wulfenite.

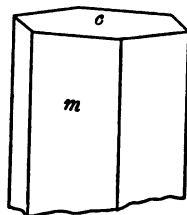


FIG. 505.

### Amblygonite, $\text{LiAl}(\text{F},\text{OH})\text{PO}_4$

**Form.** This mineral usually occurs in cleavable masses. Crystals are triclinic, but are rare and imperfect.

**Cleavage,** in two directions at angles of  $75\frac{1}{2}^\circ$ .

**H.** = 6.

**Sp. gr.**  $\pm 3.0$ .

**Color,** white or grayish white.

**Optical Properties.**  $n_r(1.59) - n_a(1.57) = 0.02$ . Fragments are irregular plates, cloudy white, and give bright interference colors. Polysynthetic twinning is common.

**Chemical Composition.** Basic lithium aluminum fluo-phosphate,  $\text{LiAl}(\text{F},\text{OH})\text{PO}_4$ . The lithium is often partly replaced by sodium. At Canon City, Colorado, a mineral with the composition  $\text{NaAl}(\text{F},\text{OH})\text{PO}_4$ , has recently been found. It has been called natramblygonite.

**Blowpipe Tests.** Easily fusible (2) with intumescence to a white opaque globule, coloring the flame red. In the closed tube water is given off and the tube is etched.

Soluble with difficulty in  $\text{H}_2\text{SO}_4$ .

**Uses.** Amblygonite is a source of lithium salts, phosphates giving a valuable by-product. It has been mined in South Dakota.

**Occurrence.** 1. In granite-pegmatites associated with lepidolite, tourmaline and spodumene. Pala, San Diego County, California, is a prominent locality.

### Olivenite, $\text{Cu}_2(\text{OH})\text{AsO}_4$

**Form.** Olivenite occurs in prismatic or acicular crystals and fibrous aggregates. The crystals are orthorhombic, but are

$n = 3$ .

**Sp. gr.**  $\pm 4.3$ .

**Color,** usually various tints and shades of green.

**Optical Properties.**  $n$  about 1.83. Fragments are acicular with parallel extinction, positive elongation, and bright interference colors.

**Chemical Composition.** Basic copper arsenate,  $\text{Cu}_2(\text{OH})\text{AsO}_4$ ;  $\text{O} = 3.2$  per cent.). It may also contain a little  $(\text{PO}_4)$ .

**Blowpipe Tests.** Easily fusible (2). In the closed tube with charcoal gives an arsenic mirror.

Soluble in  $\text{HNO}_3$ .  $(\text{NH}_4)_2\text{MoO}_4$  gives a yellow precipitate on filtering the nitric acid solution.

**Occurrence.** 1. A secondary mineral occurring with copper arsenates and phosphates. In the Tintic (Utah) district it has been formed by the oxidation of enargite,  $\text{Cu}_3\text{AsS}_4$ .

### VIVIANITE GROUP—MONOCLINIC

The following compounds are isomorphous with vivianite and schreibersite:  $\text{Fe}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$ ,  $\text{Mg}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$ ,  $\text{Mg}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$ ,  $\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$ , and  $\text{Zn}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$ . Isomorphous mixtures

are common. These minerals are all secondary, usually occurring as incrustations. Erythrite is called "cobalt bloom," while annabergite, the corresponding nickel arsenate, is called "nickel bloom."

### Vivianite, $\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$

**Form.** Vivianite occurs in small crystals, in nodules, and in earthy masses. Crystals are monoclinic with varying habit.

**Cleavage,** perfect in one direction (010).

**H.** = 2.

**Sp. gr.**  $\pm 2.6$ .

**Color,** deep blue or bluish-green, but colorless if unaltered.

**Optical Properties.**  $n_r(1.62) - n_a(1.57) = 0.05$ . Fragments are prismatic with either parallel or oblique ( $28\frac{1}{2}^\circ$ ) extinction. Pleochroic from blue to colorless or blue to green.

**Chemical Composition.** Hydrous ferrous phosphate,  $\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$ ; ( $\text{H}_2\text{O} = 28.7$  per cent.). It usually contains some ferric iron as the result of oxidation.

**Blowpipe Tests.** Easily fusible (2) to a black magnetic globule. In the closed tube gives water and whitens. It gives the borax bead test for ferrous iron, a bead made blue with  $\text{CuO}$  becoming opaque red in a neutral flame.

Soluble in  $\text{HNO}_3$  or  $\text{HCl}$ .  $(\text{NH}_4)_2\text{MoO}_4$  gives a yellow ppt.

**Occurrence.** 1. As a secondary mineral in veins associated with pyrite and pyrrhotite.

2. In clay and marl beds sometimes replacing fossils and in soils often around the roots of trees. At Mullica Hill, New Jersey, it replaces fossil belemnites.

### Erythrite, $\text{Co}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$

**Form.** This mineral occurs in minute crystals and as an incrustation.

**H.** = 2.

**Sp. gr.**  $\pm 2.9$ .

**Color,** pink to red.

**Optical Properties.**  $n_r(1.69) - n_a(1.62) = 0.07$ . Fragments are



prismatic with oblique extinction ( $31^\circ$ ) and are pleochroic from pale to deep pink.

**Chemical Composition.** Hydrous cobalt arsenate,  $\text{Co}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$ ; ( $\text{H}_2\text{O} = 24.1$  per cent.). The cobalt is sometimes replaced by nickel and iron.

**Blowpipe Tests.** Easily fusible (2) coloring the flame faint blue. In the closed tube it gives off water and turns blue. In the closed tube with charcoal gives an arsenic mirror.

Soluble in  $\text{HNO}_3$  to a pink solution. With  $(\text{NH}_4)_2\text{MoO}_4$  this solution gives a yellow ppt. on boiling.

**Occurrence.** 1. A secondary mineral on smaltite and cobaltite, and hence is called "cobalt bloom." Schneeberg, Saxony.

### Wavellite, $\text{Al}_3(\text{OH})_3(\text{PO}_4)_2 \cdot 5\text{H}_2\text{O}$

**Form.** Wavellite occurs in hemispherical or radiating crystalline aggregates and in stalactitic forms. Distinct crystals (orthorhombic) are very rare.

**H.** =  $3\frac{1}{2}$  to 4.

**Sp. gr.**  $\pm 2.3$ .

**Color,** green, white, yellow, or gray.

**Optical Properties.**  $n_g = 1.52$ . Fragments are prismatic and acicular with parallel extinction, positive elongation, and bright interference colors.

**Chemical Composition.** Hydrous basic aluminum phosphate,  $\text{Al}_3(\text{OH})_3(\text{PO}_4)_2 \cdot 5\text{H}_2\text{O}$ ; ( $\text{H}_2\text{O} = 26.8$  per cent.). Some analyses show a little fluorin.

**Blowpipe Tests.** Infusible, but swells and splits. In the closed tube it gives water. Heated with cobalt nitrate solution in the forceps it turns deep blue.

Soluble in  $\text{HCl}$ .

**Uses.** At Mount Holly Springs, Penn., wavellite has been used as a source of phosphorus.

**Occurrence.** 1. As a secondary mineral along the seams of sandstones, slates, and other rocks.

**Turquoise,  $H_5[Al(OH)_2]_6Cu(OH)(PO_4)_4$** 

**Form.** Turquoise occurs in seams and incrustations, but at one locality it has been found in minute triclinic crystals.

**H.** = 6.

**Sp. gr.**  $\pm 2.7$ .

**Color,** usually bluish-green but varies from blue to green.

**Optical Properties.**  $n$  about 1.63. Fragments are irregular, bluish or greenish with aggregate polarization in low first-order interference colors.

**Chemical Composition.** Acid and basic aluminum copper phosphate,  $H_5[Al(OH_2)]_6Cu(OH)(PO_4)_4$ , according to Schaller. ( $H_2O = 19.5$  per cent.)

**Blowpipe Tests.** Infusible, but turns dark when heated and gives a green flame which is made blue by HCl. In the closed tube at a high temperature it gives water and turns dark.

Soluble in HCl after gentle ignition.

**Uses.** Turquoise is used extensively as a gem. Blue stones are more valuable than green ones.

**Occurrence.** 1. In seams of volcanic rocks such as trachytes and rhyolites. Los Cerrillos Mts., New Mexico (in andesite).

## 10. NITRATES, BORATES, AND URANATES

Soda Niter,	$\text{NaNO}_3$
COLEMANITE,	$\text{Ca}_2\text{B}_6\text{O}_{11} \cdot 5\text{H}_2\text{O}$
Boracite,	$\text{Mg}_2\text{Cl}_2\text{B}_{10}\text{O}_{30}$
Ulexite,	$\text{NaCaB}_5\text{O}_9 \cdot 8\text{H}_2\text{O}$
Borax,	$\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$
Uraninite,	$\text{UO}_2, \text{UO}_3, \text{Pb}$ , etc.

Of the few mineral nitrates known, soda niter is the only one of importance.

Only a few borates are prominent as minerals.  $\text{H}_3\text{BO}_3$  is ortho-boric acid. Borax is a salt of  $\text{H}_2\text{B}_4\text{O}_7$  derived thus:  $4\text{H}_3\text{BO}_3 - 5\text{H}_2\text{O} = \text{H}_2\text{B}_4\text{O}_7$ . Ulexite is a salt of  $\text{H}_3\text{B}_5\text{O}_9$  ( $5\text{H}_3\text{BO}_3 - 6\text{H}_2\text{O}$ ). Colemanite is a salt of  $\text{H}_4\text{B}_6\text{O}_{11}$  ( $6\text{H}_3\text{BO}_3 - 7\text{H}_2\text{O}$ ). Boracite is  $2(\text{Mg}_3\text{B}_8\text{O}_{18}) \cdot \text{MgCl}_2$  ( $8\text{H}_3\text{BO}_3 - 9\text{H}_2\text{O} = \text{H}_6\text{B}_8\text{O}_{18}$ ). These are called tetra-, penta-, hexa-, and octo-boric acids respectively.

### Soda Niter, $\text{NaNO}_3$

**Form.** Soda niter is found in crystalline and granular masses. It crystallizes in rhombohedrons with almost the same angles as the unit or cleavage rhombohedron of calcite ( $10\bar{1}1:01\bar{1}1=73^\circ 30'$ ).

**Cleavage,** rhombohedral like calcite.

**H.**  $= 1\frac{1}{2}$  to 2.

**Sp. gr.**  $\pm 2.3$ .

**Color,** white or colorless. Very deliquescent.

**Optical Properties.**  $n_r(1.587) - n_a(1.336) = 0.251$ . The optical properties are like those of calcite. It recrystallizes from water solution in rhombic shaped crystals (Fig. 506) with symmetrical extinction and very high-order interference colors.

**Chemical Composition.** Sodium nitrate,  $\text{NaNO}_3$ . Iodin may be present in the form of  $\text{Ca}(\text{IO}_3)_2$  or lautarite, a yellow mineral.

**Blowpipe Tests.** Easily fusible (1), giving an intense yellow flame. With  $\text{KHSO}_4$  in the closed tube it gives red-brown fumes of  $\text{NO}_2$ .

Soluble in water.

**Uses.** Soda niter is used as a fertilizer and also in the manufacture of  $\text{KNO}_3$ . Chili furnishes the world's supply.

**Occurrence.** 1. In arid regions. Occurs in northern Chili and to a slight extent in California and Nevada. Soda niter is probably formed by nitrifying bacteria, which convert nitrogen and ammonia into nitrates.

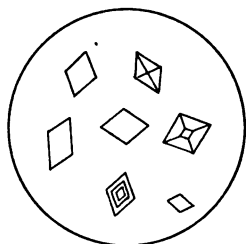


FIG. 506.—Soda niter recrystallised.

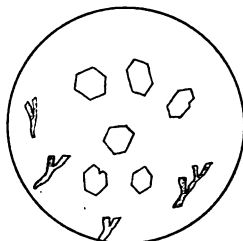


FIG. 507.—Boric acid.

### COLEMANITE, $\text{Ca}_2\text{B}_6\text{O}_{11} \cdot 5\text{H}_2\text{O}$

**Form.** Colemanite occurs in crystals, which often line geodes, and in crystalline and compact masses. The crystals are monoclinic and are often highly modified.

**Cleavage,** perfect in one direction (010).

**H.** =  $4\frac{1}{2}$ .

**Sp. gr.**  $\pm 2.4$ .

**Color,** colorless or white.

**Optical Properties.**  $n_\gamma(1.61) - n_\alpha(1.58) = 0.03$ . Fragments are irregular plates with bright interference colors. With  $\text{HCl}$  pseudo-hexagonal crystals of boric acid separate out (Fig. 507).

**Chemical Composition.** Hydrous calcium hexa-borate,  $\text{Ca}_2\text{B}_6\text{O}_{11} \cdot 5\text{H}_2\text{O}$ ; ( $\text{H}_2\text{O} = 21.9$  per cent.).

**Blowpipe Tests.** Fuses easily ( $1\frac{1}{2}$ ) with exfoliation coloring the flame green. In the closed tube gives water.

Soluble in hot HCl. Boric acid separates out on cooling.

**Uses.** Colemanite is the principal source of borax and boracic acid. It is obtained in various places in Southern California.

**Occurrence.** 1. In lake-beds interstratified with Tertiary sediments. Calico, San Bernardino County, California.

### Boracite, $\text{Mg}_7\text{Cl}_2\text{B}_{10}\text{O}_{30}$

**Form.** Occurs in small embedded isometric crystals and in granular masses which resemble marble. The crystals, which are very sharp and model-like, though small, belong to the isometric hextetrahedral class and are among the best representatives of that class obtainable. The usual forms are the cube  $a\{100\}$ , dodecahedron  $d\{110\}$ , positive tetrahedron  $o\{111\}$ , and negative tetrahedron  $o_1\{1\bar{1}1\}$ . Fig. 508 is a typical crystal.

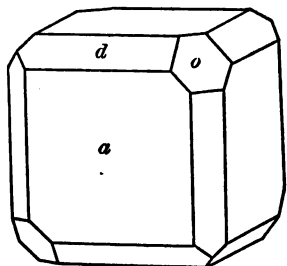


FIG. 508.

H. = 5 to 7.

Sp. gr.  $\pm 2.9$ .

**Color,** colorless or white.

**Optical Properties.**  $n_g(1.673) - n_a(1.662) = 0.011$ . Fragments are irregular with low first order interference colors and sometimes show polysynthetic twinning. Boracite, though

isometric, shows double refraction. This optical anomaly may be explained by assuming that the boracite substance is dimorphous, for the double refraction disappears at  $265^\circ \text{C}$ .

**Chemical Composition.** Magnesium chlorid octo-borate,  $\text{Mg}_7\text{Cl}_2\text{B}_{10}\text{O}_{30}$  or  $\text{MgCl}_2 \cdot 2(\text{Mg}_3\text{B}_5\text{O}_{15})$ .

**Blowpipe Tests.** Easily fusible at 2 with intumescence, coloring the flame green. With a  $\text{NaPO}_3$  bead saturated with  $\text{CuO}$  it gives an azure-blue flame. The massive variety gives water in the closed tube.

Soluble in HCl.

**Occurrence.** 1. In gypsum, anhydrite, or carnallite. Stassfurt, Germany.

**Ulexite,  $\text{NaCaB}_5\text{O}_9 \cdot 8\text{H}_2\text{O}$**

**Form.** Ulexite is found in rounded fibrous masses, locally called "cotton-balls."

**H.** = 1.

**Sp. gr.**  $\pm 1.6$ .

**Color,** white. **Luster,** silky.

**Optical Properties.**  $n = 1.51$ . Fragments are acicular with parallel extinction, negative elongation, and low first-order interference colors.

**Chemical Composition.** Hydrous sodium calcium pentaborate,  $\text{NaCaB}_5\text{O}_9 \cdot 8\text{H}_2\text{O}$ ; ( $\text{H}_2\text{O} = 35.5$  per cent.).

**Blowpipe Tests.** Easily fusible (1) with intumescence, coloring the flame an intense yellow. In closed tube gives water.

Soluble in hot  $\text{HCl}$ ,  $\text{H}_3\text{BO}_3$  separating out on cooling.

**Occurrence.** 1. In playas (the dried-up lakes of arid regions) associated with borax, gypsum, and halite. Esmeralda County, Nevada.

**Borax,  $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$**

**Form.** Borax occurs in crystals and in efflorescent crusts. The crystals are monoclinic and near pyroxene in angles and habit.

**H.** = 2.

**Sp. gr.**  $\pm 1.7$ .

**Color,** white or colorless. **Efflorescent.**

**Optical Properties.**  $n_r(1.47) - n_a(1.45) = 0.02$ . Recrystallizes from water solution in crystals having (1) low first order interference colors and oblique extinction and (2) bright interference colors and parallel extinction (see Fig. 509).

**Chemical Composition.** Hydrous sodium tetraborate,  $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ ; ( $\text{H}_2\text{O} = 47.2$  per cent.).

**Blowpipe Tests.** Easily fusible (1) to a clear glass giving an

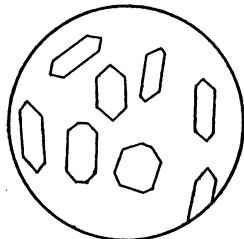


FIG. 509.  
Borax recrystallized.

intense yellow flame. A solution in alcohol burns with a green flame.

Soluble in water.

**Uses.** Borax has many uses, but most of the borax of commerce is now made from colemanite.

**Occurrence.** 1. In lake-deposits in arid regions associated with halite, trona, theuārdite, glauberite, hanksite, gypsum, etc. Searles' borax marsh, San Bernardino County, California. The borates are leached from Tertiary lake sediments in near-by hills.

### Uraninite, $\text{UO}_3$ , $\text{UO}_2$ , Pb, etc.

**Form.** Uraninite is very rarely found in isometric octahedral crystals. It is usually massive and sometimes has a botryoidal surface.

H. =  $5\frac{1}{2}$ .

Sp. gr. 7.5 to 9.5.

**Color,** dark brown to black. Luster, submetallic or pitch-like. Streak usually olive-green.

**Optical Properties.**  $n > 1.74$ . Fragments are irregular, sometimes translucent brown and isotropic, sometimes opaque.

**Chemical Composition.** Uncertain. Analyses show varying amounts of  $\text{UO}_2$ ,  $\text{UO}_3$ , Pb, and Th. Also contains helium and radium.

**Blowpipe Tests.** Infusible. The  $\text{NaPO}_3$  bead is yellowish-green in O.F. and green in R.F.

Soluble in  $\text{HNO}_3$ . With  $\text{NH}_4\text{OH}$  the solution gives a yellow precipitate.

**Uses.** Uraninite is the source of uranium compounds and also of radium compounds.

**Occurrence.** 1. In veins with metallic sulfids. Joachimsthal, Bohemia.

2. In granite-pegmatites. Llano County, Texas.

## 11. SULFATES

### *A. Normal Anhydrous Sulfates*

Barite Group	{	BARITE,	BaSO <sub>4</sub>
		CELESTITE,	SrSO <sub>4</sub>
		ANGLESITE,	PbSO <sub>4</sub>
		ANHYDRITE,	CaSO <sub>4</sub>
		Crocoite,	PbCrO <sub>4</sub>

### *B. Basic and Hydrous Sulfates*

Kainite,	MgSO <sub>4</sub> ·KCl·3H <sub>2</sub> O
Brochantite,	Cu <sub>2</sub> (OH) <sub>2</sub> SO <sub>4</sub>
Mirabilite,	Na <sub>2</sub> SO <sub>4</sub> ·10H <sub>2</sub> O
GYPSUM,	CaSO <sub>4</sub> ·2H <sub>2</sub> O
Epsomite,	MgSO <sub>4</sub> ·7H <sub>2</sub> O
Melanterite,	FeSO <sub>4</sub> ·7H <sub>2</sub> O
Chalcanthite,	CuSO <sub>4</sub> ·5H <sub>2</sub> O
Copiapite,	Fe <sub>3</sub> (OH) <sub>2</sub> (SO <sub>4</sub> ) <sub>6</sub> ·17H <sub>2</sub> O
Alunite,	KAl <sub>3</sub> (OH) <sub>6</sub> (SO <sub>4</sub> ) <sub>2</sub>

A large number of sulfate minerals, most of them basic and hydrous salts, are known but comparatively few are of much importance. They are all salts of H<sub>2</sub>SO<sub>4</sub>. No sulfites, pyrosulfates, thiosulfates, or persulfates are known among minerals.

### BARITE GROUP—ORTHORHOMBIC

In habit, angles, and cleavage barite, celestite, and anglesite are similar, and thus constitute an isomorphous group. One would expect to find anhydrite in this group, but it differs in angles and especially in cleavage. There are isomorphous mixtures of BaSO<sub>4</sub> and SrSO<sub>4</sub>, but they do not seem to mix with PbSO<sub>4</sub>.



**BARITE,  $\text{BaSO}_4$** 

**Form.** Barite occurs in crystals, in crested groups, in lamellar, nodular, fibrous, and granular masses.

Rhombic bipyramidal class:  $a:b:c=0.815:1:1.313$ . Usual forms:  $c\{001\}$ ,  $m\{110\}$ ,  $o\{011\}$ ,  $d\{102\}$ ,  $l\{104\}$ ,  $z\{111\}$ ,  $y\{122\}$ . Interfacial angles:  $mm(110:1\bar{1}0)=78^\circ 22\frac{1}{2}'$ ;  $co(001:011)=52^\circ 43'$ ;  $cd(001:102)=38^\circ 51\frac{1}{2}'$ ;  $cl(001:104)=21^\circ 56\frac{1}{2}'$ ;  $cz(001:111)=64^\circ 19'$ ;  $oy(011:122)=26^\circ 1'$ . The habit is usually tabular parallel to  $\{001\}$ , as represented in Figs. 510 to 513, but prismatic crystals are also common.

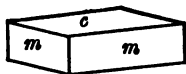


FIG. 510.

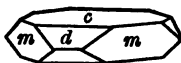


FIG. 511.

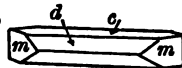


FIG. 512.



FIG. 513.

**Cleavage**, parallel to  $c\{001\}$  and to  $m\{110\}$ . The cleavage form is like Fig. 510, with two right angles and one oblique angle ( $78^\circ 22'$ ).

**H.** = 3.

**Sp. gr.**  $\pm 4.5$ .

**Color**, colorless, white, and almost any color.

**Optical Properties.**  $n_r(1.647) - n_a(1.636) = 0.011$ . Fragments are rhombic with symmetrical extinction or rectangular with parallel extinction. The interference colors are bright.

**Chemical Composition.** Barium sulfate  $\text{BaSO}_4$ ; (Ba = 58.8 per cent.). Sr and Ca often replace part of the Ba.

**Blowpipe Tests.** Fusible (4) coloring the flame yellowish-green. Unaltered in the closed tube, but usually decrepitates. The water solution of the soda fusion gives a white precipitate with  $\text{BaCl}_2$ , which is insoluble in HCl.

Insoluble in acids.

**Uses.** Barite is used in the manufacture of paint as a substitute for white lead.

**Occurrence.** 1. As a gangue mineral in veins, especially with lead ores.

2. As lenticular masses in residual clays overlying limestones. These masses have probably been formed by the metasomatic replacement of limestone. Washington County, Missouri.

3. As a secondary mineral in cavities of limestone. It sometimes replaces fossils.

### CELESTITE, $\text{SrSO}_4$

**Form.** Celestite occurs in crystals, in cleavable masses, and in fibrous seams. The crystals are like barite in habit, forms, and angles. Crystals one and a half feet in length have been found on the Island of Put-In-Bay, Lake Erie.

**Cleavage,** perfect parallel to {001} and imperfect parallel to {110}. The imperfect prismatic cleavage distinguishes celestite from barite.

**H.** = 3.

**Sp. gr.**  $\pm 3.9$ .

**Color,** colorless, white, pale blue, and sometimes red.

**Optical Properties.**  $n_r(1.631) - n_a(1.622) = 0.009$ . Fragments are like those of barite.

**Chemical Composition.** Strontium sulfate,  $\text{SrSO}_4$ ; (Sr = 47.7 per cent.). Sometimes Ca and Ba are present.

**Blowpipe Tests.** Fusible (4) giving a crimson red flame especially with HCl. The water solution of the soda fusion gives a white precipitate with  $\text{BaCl}_2$ , which is insoluble in HCl.

Insoluble in acids.

**Uses.** Celestite is used to some extent in the manufacture of fire-works.

**Occurrence.** 1. As a secondary mineral in limestone. Near Austin, Texas.

2. With sulfur and gypsum in marl. Girgenti, Sicily.

### ANGLESITE, $\text{PbSO}_4$

**Form:** There are two characteristic occurrences of anglesite, in crystals in cavities, and in masses with a banded structure. The crystals are orthorhombic and of varied habit. See Figs

514, 515, and 516, in which  $m\{110\}$ ,  $a\{100\}$ ,  $c\{001\}$ ,  $d\{102\}$ ,  $o\{011\}$ ,  $z\{111\}$ ,  $y\{122\}$ . Anglesite can usually be recognized (also distinguished from cerussite) by the resemblance to barite crystals, the angles being almost the same as for barite. Unlike cerussite it never occurs in twin-crystals.

**Cleavage**, imperfect and not important.

**H.** = 3.

**Sp. gr.**  $\pm 6.3$ .

**Color**, colorless, white, or gray. Luster, adamantine.

**Optical Properties.**  $n_r(1.893) - n_a(1.877) = 0.016$ . Fragments

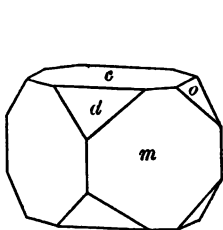


FIG. 514.

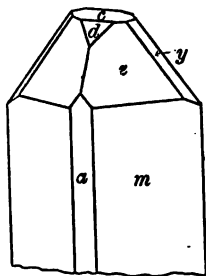


FIG. 515.

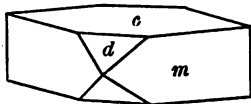


FIG. 516.

are irregular with bright interference colors (cerussite has very high-order colors).

**Chemical Composition.** Lead sulfate,  $\text{PbSO}_4$ ; (Pb = 68.3 per cent.).

**Blowpipe Tests.** Easily fusible ( $1\frac{1}{2}$ ) on charcoal to a white globule. In R.F. on charcoal gives a metallic button.

Soluble in  $\text{HNO}_3$  with difficulty. Soluble in  $\text{NH}_4\text{C}_2\text{H}_3\text{O}_2$  (made by neutralizing acetic acid with ammonia).

**Uses.** Anglesite is one of the minor ores of lead.

**Occurrence.** 1. As a secondary mineral in lead mines or in the gossan of veins. It often accompanies cerussite and is sometimes pseudomorphous after galena. Phoenixville, Pennsylvania.

**ANHYDRITE,  $\text{CaSO}_4$** 

**Form.** Anhydrite occurs in cleavable and granular masses and but rarely in orthorhombic crystals.

**Cleavage,** in three directions at right angles (pseudo-cubic).

**H.** = 3 to  $3\frac{1}{2}$ .

**Sp. gr.**  $\pm 2.9$ .

**Color,** colorless, white, gray, bluish, or reddish. Luster, pearly on cleavage faces.

**Optical Properties.**  $n_\gamma(1.61) - n_\alpha(1.57) = 0.04$ . Fragments are square and rectangular with parallel extinction and bright interference colors. There are often twinning striations parallel to the diagonals of the squares. With dilute HCl microchemical gypsum is formed (Fig. 387, p. 198).

**Chemical Composition.** Calcium sulfate,  $\text{CaSO}_4$ ; (Ca = 29.4 per cent.).

**Blowpipe Tests.** Fuses (3) and colors flame yellowish-red. In the closed tube may yield a little water due to partial hydration to gypsum.

Soluble with difficulty in HCl.

**Occurrence.** 1. In salt mines as the direct deposition of seawater. Ellsworth County, Kansas.

2. In cavities in limestone. Lockport, New York.

3. In veins or vein-like deposits. Shasta County, California.

**Crocoite,  $\text{PbCrO}_4$** 

**From.** Crocoite is found in prismatic (monoclinic) crystals of nearly square cross section and in columnar aggregates.

**H.** = 3.

**Sp. gr.**  $\pm 6.0$ .

**Color,** red. Streak, orange. Luster, adamantine.

**Optical Properties.**  $n_\beta = 2.4$ . Double refraction very strong. Fragments are prismatic with parallel extinction, very high order interference colors, and pleochroism from yellow to red.

**Chemical Composition.** Lead chromate,  $\text{PbCrO}_4$ ; (Pb = 64.1 per cent.).

**Blowpipe Tests.** Easily fusible ( $1\frac{1}{2}$ ) on charcoal giving a metallic button. In the closed tube turns dark and decrepitates.

**Occurrence.** 1. A secondary mineral in the gossan. Near Dundas, Tasmania, crocoite occurs in a limonite matrix.

### Kainite, $\text{MgSO}_4 \cdot \text{KCl} \cdot 3\text{H}_2\text{O}$

**Form.** Kainite usually occurs in granular masses.

**H.** =  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 2.1$ .

**Color,** white, colorless or reddish.

**Optical Properties.**  $n_r(1.52) - n_a(1.49) = 0.03$ . Recrystallizes from water solution in the following order: (1)  $\text{K}_2\text{Mg}(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}$ , prismatic crystals with oblique extinction. (2) KCl, isotropic squares. (3)  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$  and  $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$ , confused streaky aggregates. Fig. 517 represents the three stages of crystallization. The equation is  $3\text{MgSO}_4 \cdot \text{KCl} = \text{K}_2\text{Mg}(\text{SO}_4)_2 + \text{KCl} + \text{MgSO}_4 + \text{MgCl}_2$  (water is omitted).



FIG. 517.  
Kainite recrystallized.

**Chemical Composition.** Hydrrous magnesium sulfate and potassium chlorid.  $\text{MgSO}_4 \cdot \text{KCl} \cdot 3\text{H}_2\text{O}$ ; ( $\text{H}_2\text{O} = 21.7$  per cent.).

**Blowpipe Tests.** Easily fusible (2) coloring the flame violet. In the closed tube gives water.

Soluble in water. The solution gives wet tests for Mg,  $\text{SO}_4$ , and Cl.

**Uses.** Kainite is used extensively as a fertilizer and as a source of potassium salts.

**Occurrence.** 1. A secondary mineral of the Stassfurt salt deposits resulting from the action of magnesium sulfate on carnallite.

### Brochantite, $\text{Cu}_4(\text{OH})_6\text{SO}_4$

**Form.** Brochantite is found in small prismatic crystals, in drusy crusts, and in fibrous masses.

**H.** =  $3\frac{1}{2}$ .

**Sp. gr.**  $\pm 3.9$ .

**Color,** green.

**Optical Properties.**  $n_r > 1.74$ ,  $n_a < 1.74$ . Fragments are prismatic with parallel extinction.

**Chemical Composition.** Basic copper sulfate,  $\text{Cu}_4(\text{OH})_6 \text{SO}_4$  or  $\text{CuSO}_4 \cdot 3\text{Cu}(\text{OH})_2$ ; ( $\text{H}_2\text{O} = 12$  per cent.).

**Blowpipe Tests.** Fusible at  $3\frac{1}{2}$ . In the closed tube turns black and gives off water.

Insoluble in water. Soluble in  $\text{HNO}_3$  *without* effervescence (distinction from malachite, which it greatly resembles).

**Occurrence.** 1. A secondary mineral associated with other copper minerals. Morenci, Arizona.

### Mirabilite, $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$

**Form.** In crusts and as a powder. Crystals are very rare.

**H.**  $1\frac{1}{2}$  to 2.

**Sp. gr.**  $\pm 1.5$ .

**Color,** white.

**Optical Properties.**  $n$  about 1.44. Recrystallizes from a water solution in long prismatic crystals with low first order interference colors and parallel extinction (Fig. 518).

**Chemical Composition.** Hydrour sodium sulfate,  $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ ; ( $\text{H}_2\text{O} = 55.9$  per cent.).

**Blowpipe Tests.** Easily fusible ( $1\frac{1}{2}$ ) giving an intense yellow flame. In the closed tube gives abundant water.

Soluble in water.

**Occurrence.** 1. In soda lakes. It forms along the shores of Great Salt Lake in Utah during the winter.

2. As an efflorescence in caves and other protected places.

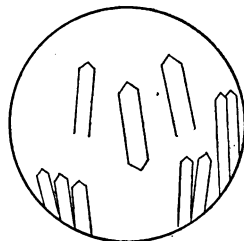


FIG. 518.  
Mirabilite recrystallized.

### GYP SUM, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$

**Form.** In form gypsum is variable. It occurs in embedded and attached crystals, in cleavable and crystalline masses, and in fibrous and granular masses.

Monoclinic system, prismatic class.  $a:b:c=0.690:1:0.412$ ;  $\beta=80^\circ 42'$ . Usual forms:  $m\{110\}$ ,  $l\{111\}$ ,  $b\{010\}$ ,  $e\{\bar{1}03\}$ . Interfacial angles:  $mm(110:\bar{1}\bar{1}0)=68^\circ 30'$ ;  $ll(111:\bar{1}\bar{1}1)=36^\circ 12'$ ;  $ml(110:111)=49^\circ 9'$ ;  $ae(\text{edge } \bar{1}\bar{1}0-\bar{1}\bar{1}0:\bar{1}03)=87^\circ 49'$ . The habit is usually tabular parallel to the side pinacoid  $\{010\}$ . Figs. 519 to 521 represent typical crystals.

Twins with  $\{100\}$  as twin-plane are common (Fig. 522).

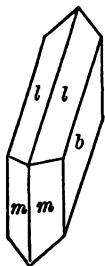


FIG. 519.

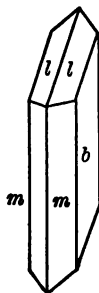


FIG. 520.

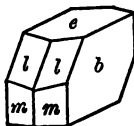


FIG. 521.

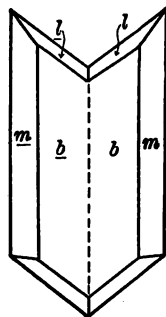


FIG. 522.

**Cleavage**, perfect in one direction parallel to  $\{010\}$ , also imperfect conchoidal parallel to  $\{100\}$  and fibrous parallel to  $\{\bar{1}11\}$ . A cleavage fragment is oriented with respect to the crystal outline as shown in Fig. 306 (p. 105).

**H.**  $\approx 2$ .

**Sp. gr.**  $\pm 2.3$ .

**Color**, colorless, white, amber, gray, pink, etc. Luster, vitreous, silky, or pearly.

**Optical Properties.**  $n_r(1.529) - n_a(1.520) = 0.009$ . Fragments are prismatic or acicular or platy with bright interference colors and extinction angles of  $0^\circ$ ,  $13\frac{1}{2}^\circ$ , or  $37\frac{1}{2}^\circ$ . Recrystallizes from dilute HCl solution as microchemical gypsum (Fig. 387, p. 198).

**Chemical Composition.** Hydrous calcium sulfate,  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ; ( $\text{H}_2\text{O} = 20.9$  per cent.). Massive gypsum may contain  $\text{CaCO}_3$ , clay, sand, or organic matter.

**Blowpipe Tests.** Easily fusible (3) to a white enamel giving

a yellow-red flame. In the closed tube becomes opaque and gives off water at a low temperature.

Easily soluble in dilute HCl (distinction from anhydrite).

**Uses.** Gypsum is extensively used in the manufacture of plaster and as a fertilizer.

**Occurrence.** 1. In bedded deposits associated with salt and limestone and formed directly by the evaporation of inland seas.

2. As a secondary mineral in various rocks, formed principally by the action of sulfuric acid or ferrous sulfate (produced by the oxidation of pyrite) on calcium carbonate.

3. As a hydration product of anhydrite. At the Ludwig mine in Lyon County, Nevada, the hydration has reached a depth of 400 feet.

### Epsomite, $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$

**Form.** Epsomite is found in fibrous masses, in crusts, and occasionally in prismatic crystals belonging to the bisphenoidal class of the orthorhombic system. Fig. 81 (p. 31) represents a typical crystal.

H. = 2 to  $2\frac{1}{2}$ .

Sp. gr.  $\pm 1.7$ .

Color, colorless or white.

**Optical Properties.**  $n_r(1.46) - n_a(1.43) = 0.03$ . Recrystallizes from a water solution in prismatic crystals with parallel extinction and low first order interference colors (Fig. 523).

**Chemical Composition.** Hydrous magnesium sulfate,  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ ; ( $\text{H}_2\text{O} = 51.2$ .)

**Blowpipe Tests.** Easily fusible (1). It gives abundant water in the closed tube.

Soluble in water.

**Occurrence.** 1. As an efflorescence in abandoned mine drifts, caves, and other protected places. New Almaden, California.

2. In lake deposits. Large deposits occur in Albany County, Wyoming, along with mirabilite.



FIG. 523.  
Epsomite recrystallized.



**Melanterite,  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$** 

**Form.** Melanterite usually occurs in fibrous crusts or in capillary crystals.

**H.** = 2.

**Sp. gr.**  $\pm 1.9$ .

**Color,** white or pale green, becoming yellow on exposure.

**Optical Properties.**  $n_r(1.49) - n_a(1.47) = 0.02$ . Recrystallizes from a water solution in long prismatic crystals with parallel extinction and low first order interference colors (like epsomite, Fig. 523).

**Chemical Composition.** Hydrous ferrous sulfate,  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ ; ( $\text{H}_2\text{O} = 45.3$  per cent.). It may also contain Mg, Mn, Cu, and ferric iron.

**Blowpipe Tests.** Easily fusible (1). In the closed tube gives water which has an acid reaction. On charcoal R.F. gives a magnetic residue.

Soluble in water.

**Occurrence.** 1. A secondary mineral usually formed by the oxidation of pyrite or marcasite. Cabinet specimens of these minerals sometimes go to pieces because of their alteration to melanterite and sulfuric acid.

**Chalcanthite,  $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$** 

**Form.** Chalcanthite occurs as an incrustation or as fibrous seams. Artificial crystals of this substance furnish us among the best examples of triclinic crystals.

**H.** =  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 2.2$ .

**Color,** blue.

**Optical Properties.**  $n_r(1.54) - n_a(1.51) = 0.03$ . Recrystallizes from water solution in pale blue prismatic crystals with oblique extinction ( $10^\circ$  to  $15^\circ$ ).

**Chemical Composition.** Hydrous copper sulfate,  $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ ; ( $\text{H}_2\text{O} = 36.1$  per cent.). It often contains iron.

**Blowpipe Tests.** Fusible at 3. In the closed tube turns white, then black, yielding abundant water.

Soluble in water. The water solution placed on metallic iron (knife-blade) gives a film of copper.

**Occurrence.** 1. A secondary mineral often found in abandoned mine drifts. Butte, Montana.

**Copiapite,  $\text{Fe}_4(\text{OH})_2(\text{SO}_4)_6 \cdot 17\text{H}_2\text{O}$**

**Form.** This mineral usually occurs in granular masses or as an incrustation.

**H.** =  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 2.1$ .

**Color,** yellow. Taste, metallic astringent.

**Optical Properties.**  $n_r(1.572) - n_a(1.527) = 0.045$ . Fragments are irregular or plates with bright interference colors and are pleochroic, changing from pale to deep yellow.

**Chemical Composition.** Hydrous basic ferric sulfate,  $\text{Fe}_4(\text{OH})_2(\text{SO}_4)_6 \cdot 17\text{H}_2\text{O}$ ; ( $\text{H}_2\text{O} = 31.1$  per cent.).

**Blowpipe Tests.** Fusible with difficulty (5). In the closed tube yields water which has an acid reaction and leaves a dark red residue ( $\text{Fe}_2\text{O}_3$ ). On charcoal R.F. becomes magnetic.

Partially soluble in water. On boiling the water solution,  $\text{Fe}(\text{OH})_3$  is precipitated.

**Occurrence.** 1. A secondary mineral formed by the oxidation of pyrite or marcasite. Large deposits occur in the desert regions of Chili near Copiapo. The name was derived from this locality.

**Alunite,  $\text{KAl}_3(\text{OH})_6(\text{SO}_4)_2$**

**Form.** Alunite occurs in cavities of a siliceous rock or disseminated through the rock mass. The crystals are very small and belong to the hexagonal system. The habit is usually tabular with the pinacoid {0001} and the rhombohedron  $\{10\bar{1}1\}$ .

**H.** = 4.

**Sp. gr.**  $\pm 2.8$ .

**Color,** colorless, white, or gray.

**Optical Properties.**  $n_\gamma(1.59) - n_\alpha(1.57) = 0.02$ . Fragments are irregular with bright interference colors. Small crystals are triangular, dark between crossed nicols (basal sections), and give a positive uniaxial interference figure in convergent light.

**Chemical Composition.** Basic potassium aluminum sulfate,  $K_2SO_4 \cdot Al_2(SO_4)_3 \cdot 4Al(OH)_3$ ; ( $H_2O = 13.0$  per cent.).

**Blowpipe Tests.** Infusible and turns blue with cobalt nitrate solution. In the closed tube gives water which has an acid reaction.

Soluble in  $H_2SO_4$ .

**Uses.** Alum is obtained from the alunite rock by roasting and leaching with water.

**Occurrence.** 1. In cavities of trachytes and rhyolites, and as a metasomatic replacement of these rocks. Alunite is formed by the action of sulphurous vapors on orthoclase. Musa, Hungary.

## 12. TUNGSTATES AND MOLYBDATES

Wolframite	{	Wolframite, (Fe,Mn)WO <sub>4</sub>
Group		Hübnerite, (Mn,Fe)WO <sub>4</sub>
Scheelite	{	Scheelite, CaWO <sub>4</sub>
Group		Wulfenite, PbMoO <sub>4</sub>

### WOLFRAMITE GROUP—MONOCLINIC

	Fe	Mn	WO <sub>4</sub>
Wolframite .....	14.5	3.2	83.0
Wolframite .....	7.4	11.1	81.0
Hübnerite .....	1.1	17.9	80.4

### Wolframite, (Fe,Mn)WO<sub>4</sub>

**Form.** Wolframite occurs in crystals and in crystalline aggregates. The crystals are monoclinic and are usually tabular parallel to {100}.

**Cleavage,** perfect in one direction parallel to {010}.

**H.** = 5 to 5½.

**Sp. gr.** ± 7.4.

**Color,** black or dark brown. Luster, sub-metallic. Opaque.

**Chemical Composition.** Iron-manganese tungstate, (Fe,Mn)WO<sub>4</sub>, with iron predominating.

**Blowpipe Tests.** Fusible (3) to a magnetic globule. The soda fusion is bluish-green (Mn).

Soluble in aqua regia with the separation of WO<sub>3</sub>, a yellow residue.

**Uses.** Wolframite is the principal source of tungsten.

**Occurrence.** 1. A vein mineral especially in tin-stone veins associated with cassiterite, scheelite, etc. Zinnwald, Bohemia.

**~~Wolframite~~, (Mn,Fe)WO<sub>4</sub>**

~~Wolframite~~ usually occurs in bladed crystalline aggregates.

~~Wolframite~~ section parallel to the length.

Sp. gr.  $\pm 7.2$ .

~~Wolframite~~ Luster, sub-metallic.

~~Wolframite~~  $n > 1.66$ ,  $n < 1.74$ . Fragments are prismatic.

~~Wolframite~~ **Composition.** Manganese-iron tungstate, (Mn,Fe)WO<sub>4</sub>, manganese predominating.

~~Wolframite~~ Fusible at 4. Gives the Mn bead tests.

~~Wolframite~~ The soda fusion gives a yellow residue.

~~Wolframite~~ A vein mineral often associated with scheelite.

**SCHEELITE GROUP—TETRAGONAL**

Along with WO<sub>4</sub> and PbMoO<sub>4</sub>, there are also CuWO<sub>4</sub>, CaMoO<sub>4</sub>, and PbWO<sub>4</sub>, which are similar crystallographically. Isomorphous relations are illustrated by the following analyses:

	Ca	Pb	WO <sub>4</sub>	MoO <sub>4</sub>	Misc.
<del>Wolframite</del>	13.8	....	89.9	0.4	
<del>Wolframite</del>	14.5	....	80.3	9.1	
<del>Wolframite (pyromorphite)</del>	12.9	....	81.7	....	Cu=2.6; SiO <sub>2</sub> =0.7
<del>Wolframite</del>	0.9	53.7	....	43.8	Cu=0.3; Al <sub>2</sub> O <sub>3</sub> +Fe <sub>2</sub> O <sub>3</sub> =0.5

**Scheelite, CaWO<sub>4</sub>**

~~Scheelite~~ Scheelite occurs in both crystals and massive form. Crystals are tetragonal and belong to the tetragonal bipyramidal class and have one plane of symmetry, which is the horizontal. The habit is pyramidal with {111} or {101} as the dominant form. Angles: (111:111)=79° 55½'; (101:011)=72° 40½'.

~~Scheelite~~ cleavage, distinct parallel to {111} (in four directions).

**H.** =  $4\frac{1}{2}$  to 5.

**Sp. gr.**  $\pm 6.0$ .

**Color**, white, gray, or pale colors. Luster, sub-adamantine.

**Optical Properties.**  $n_r(1.93) - n_a(1.92) = 0.01$ . Fragments are irregular with bright interference colors.

**Chemical Composition.** Calcium tungstate,  $\text{CaWO}_4$ ; (Ca = 16.9 per cent.). The tungsten is often partly replaced by molybdenum and the calcium by copper.

**Blowpipe Tests.** Fusible with difficulty (5). The  $\text{NaPO}_3$  bead is blue in R.F.

Decomposed by HCl with the separation of a yellow residue ( $\text{WO}_3$ ) which is soluble in  $\text{NH}_4\text{OH}$ .

**Uses.** Scheelite is one source of tungsten.

**Occurrence.** 1. In veins, especially in tin-stone veins with cassiterite, fluorite, topaz, etc.

### Wulfenite, $\text{PbMoO}_4$

**Form.** Wulfenite usually occurs in crystals which are tetragonal and usually tabular in habit. Fig. 524 is a plan of the common type of crystal with  $c\{001\}$  and  $u\{102\}$ .

**H.** = 3.

**Sp. gr.**  $\pm 6.7$ .

**Color**, yellow, orange, or red. Luster, adamantine.

**Optical Properties.\***  $n_r(2.40) - n_a(2.30) = 0.10$ . Fragments are irregular and yellow with rather high interference colors. Thin tabular crystals give a negative uniaxial interference figure in convergent light.

**Chemical Composition.** Lead molybdate,  $\text{PbMoO}_4$ ; (Pb = 56.4 per cent.).

**Blowpipe Tests.** Easily fusible (2) on charcoal giving a metallic button. The  $\text{NaPO}_3$  bead is green in R.F.

Decomposed by HCl.

**Uses.** Wulfenite and molybdenite are sources of molybdenum.

**Occurrence.** 1. A secondary mineral in veins, often associated with vanadinite. Yuma County, Arizona.

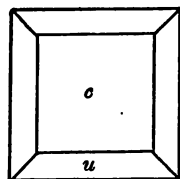


FIG. 524.

### 13. SILICATES

About a fourth of the known minerals are silicates, though many of them are very rare. They are the most important rock-forming minerals and thus make up the bulk of the earth's crust. Among the important rock-making minerals are the feldspars, the pyroxenes, the amphiboles, and the micas. These, together with quartz, constitute about 87 per cent. of the solid crust of the earth according to F. W. Clarke, while the feldspars alone constitute about 60 per cent. of the earth's crust.

Many of the silicates are complex in composition and the establishment of chemical formulæ of some of them has baffled the skill of many eminent chemists. In a chemical discussion of the silicates the starting point is  $\text{H}_4\text{SiO}_4$ , which is called orthosilicic acid. The compound  $\text{H}_2\text{SiO}_3$ , derived thus ( $\text{H}_4\text{SiO}_4 - \text{H}_2\text{O} = \text{H}_2\text{SiO}_3$ ) is called metasilicic acid. A large number of orthosilicates and metasilicates are known among minerals, but many silicates cannot be placed in either of these divisions. So the assumption has been made that other silicic acids are possible. Among them are  $\text{H}_6\text{Si}_2\text{O}_7$  ( $2\text{H}_4\text{SiO}_4 - \text{H}_2\text{O}$ ), diorthosilicic acid;  $\text{H}_2\text{Si}_2\text{O}_5$  ( $\text{H}_2\text{SiO}_3 + \text{SiO}_2$ ), dimetasilicic acid. In a similar way  $\text{H}_4\text{Si}_3\text{O}_8$ ,  $\text{H}_6\text{Si}_3\text{O}_{10}$ ,  $\text{H}_8\text{Si}_4\text{O}_{13}$  and  $\text{H}_{10}\text{Si}_5\text{O}_{16}$  may be derived. Minerals corresponding to all these acids are known.

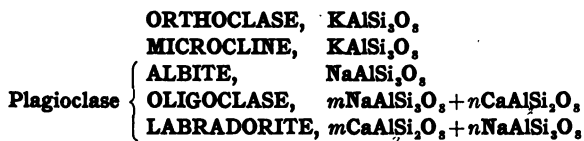
Another method formerly used by chemists, and still employed by metallurgists is based upon the ratio of the oxygen of silica in that of the bases.  $\text{R}_2\text{SiO}_4$  may be written  $2\text{RO} \cdot \text{SiO}_2$ . Here the oxygen ratio is 1:1, so orthosilicates are called unisilicates. Metasilicates,  $\text{RSiO}_3$  or  $\text{RO} \cdot \text{SiO}_2$ , are called bisilicates. Polysilicates have the formula  $\text{RO} \cdot n\text{SiO}_2$  and subsilicates,  $n\text{RO} \cdot \text{SiO}_2$ , where  $n$  is greater than 2.

The difficulty of assigning formulæ to many silicate minerals lies in the fact that it is often difficult to decide upon the valence

and grouping of the basic elements. Many silicates give water when heated in a closed tube, but it is often difficult and sometimes impossible to determine whether hydroxyl (OH), hydrion (H), or so-called water of crystallization ( $H_2O$ ) is present.  $H_2Zn_2SiO_5$  is the empirical formula for the mineral calamine. It may be an acid oxy-orthosilicate,  $H_2(Zn_2O)SiO_4$ ; a basic metasilicate,  $Zn_2(OH)_2SiO_3$ ; or an acid salt of  $H_6SiO_6$ , one of the possible silicic acids. Serpentine  $H_4Mg_3Si_2O_{10}$  presents a similar problem, for it may be written  $H_2Mg_3(SiO_4)_2 \cdot H_2O$ ,  $H_3Mg_3OH(SiO_4)_2$ ,  $H_2Mg_3(OH)_2Si_2O_7$ , or  $Mg_3Si_2O_7 \cdot 2H_2O$ .

The silicates may be conveniently divided into five groups as follows: A. Feldspars, salts of  $H_4Si_3O_8$  and isomorphous mixtures of these salts with the orthosilicate  $CaAl_2Si_2O_8$ ; B. Metasilicates; C. Orthosilicates; D. Miscellaneous anhydrous silicates, and E. Hydrous silicates.

### A. FELDSPARS



The following are typical analyses of the various feldspars:

Analyses of the Feldspars

	K <sub>2</sub> O	Na <sub>2</sub> O	CaO	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Misc.
Orthoclase .....	11.7	4.3	0.5	18.8	64.6	BaO = 0.4; ign = 0.1
Adularia .....	14.0	1.0	1.3	17.9	65.7	Fe <sub>2</sub> O <sub>3</sub> = tr.
Microcline .....	13.5	1.6	.....	19.6	64.8	ign. = 0.2
Albite .....	0.5	11.1	0.4	19.3	68.8	Fe <sub>2</sub> O <sub>3</sub> = 0.1
Oligoclase .....	1.3	8.5	4.8	23.8	61.3	Fe <sub>2</sub> O <sub>3</sub> = 0.4
Andesine .....	1.0	6.2	8.1	26.6	58.0	
Labradorite .....	tr	4.4	12.0	29.6	54.2	MgO = 0.1; ign. = 0.1
Bytownite .....	0.6	1.8	16.1	31.1	46.9	Fe <sub>2</sub> O <sub>3</sub> = 1.3; H <sub>2</sub> O = 1.0
Anorthite .....	.....	0.2	19.3	36.8	44.0	MgO = 0.2; ign. = 0.1



### ORTHOCLASE, $\text{KAlSi}_3\text{O}_8$

**Form.** Orthoclase occurs in attached and embedded crystals, in cleavable masses, and disseminated through rock masses. Orthoclase is one of the best examples of the monoclinic prismatic class. Axial ratio:  $a:b:c=0.658:1:0.555$ ;  $\beta=63^\circ 57'$ . Usual forms:  $c\{001\}$ ,  $b\{010\}$ ,  $x\{\bar{1}01\}$ ,  $y\{\bar{2}01\}$ ,  $m\{110\}$ ,  $z\{130\}$ ,  $o\{\bar{1}11\}$ ,

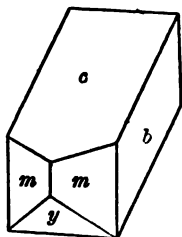


FIG. 525.

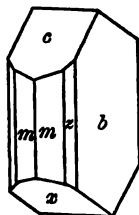


FIG. 526.

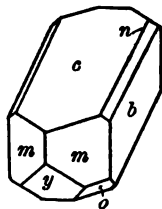


FIG. 527.

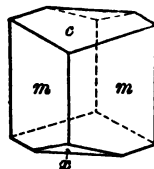


FIG. 528.

$n\{021\}$ . Interfacial angles:  $bc(010:001)=90^\circ 0'$ ;  $mm(110:\bar{1}\bar{1}0)=61^\circ 13'$ ;  $mc(110:001)=67^\circ 47'$ ;  $cx(001:\bar{1}01)=50^\circ 16\frac{1}{2}'$ ;  $cy(001:\bar{2}01)=80^\circ 18'$ ;  $mz(110:130)=29^\circ 59\frac{1}{2}'$ ;  $bo(010:\bar{1}11)=63^\circ 8'$ ;  $cn(001:021)=44^\circ 56\frac{1}{2}'$ . The habit is usually elongate in the direction of the  $a$ -axis (Figs. 525, 527) or elongate in the direction

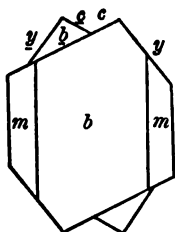


FIG. 529.

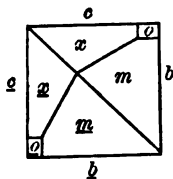


FIG. 530.

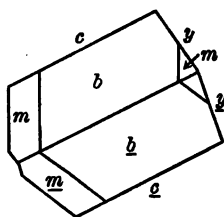


FIG. 531.

of the  $c$ -axis and tabular parallel to  $\{010\}$  (Fig. 526). Fig. 528 is prismatic and pseudo-orthorhombic.

There are three common twinning laws for orthoclase: (1) the Carlsbad law in which the  $c$ -axis is the twin-axis (usually penetration twins with  $b\{010\}$  as the composition face), (2) the

Baveno law in which  $n\{021\}$  is the twin-plane and (3) the Manebach law in which  $c\{001\}$  is the twin-plane. These three types of twinning are represented by Figs. 529–531.

**Cleavage** in two directions at right angles parallel to  $\{001\}$  and  $\{010\}$ . There is also imperfect cleavage or parting parallel to  $\{110\}$  which assists in orienting cleavages and imperfect crystals.

**H.** = 6.

**Sp. gr.**  $\pm 2.57$ .

**Color**, white, colorless, gray, pink, red. Sometimes has a play of colors.

**Optical Properties.**  $n_r(1.526) - n_a(1.519) = 0.007$ . Fragments are plates, usually with one set of parallel straight edges (Fig. 532). The interference colors are middle first order (gray and straw-yellow).

**Chemical Composition.** Potassium aluminum trisilicate,  $\text{KAlSi}_3\text{O}_8$ ; ( $\text{K}_2\text{O} = 16.9$ ,  $\text{Al}_2\text{O}_3 = 18.4$ ,  $\text{SiO}_2 = 64.7$ ). Sodium usually replaces part of the potassium.

**Blowpipe Tests.** Fusible with difficulty (5).

Insoluble in ordinary acids.

**Uses.** Orthoclase, and also microcline, Orthoclase fragments. is used in the manufacture of porcelain and china. A variety called moonstone is used as a gem.

**Occurrence.** 1. In acid plutonic igneous rocks, especially granites and syenites.

2. In acid volcanic igneous rocks, rhyolites and trachytes. This is usually sanidine, a glassy variety of orthoclase.

3. In certain rare basic igneous rocks.

4. In gneisses, partly as a remnant of igneous rocks, partly recrystallized.

5. In cavities and seams of schists and gneisses. This is the variety adularia, a transparent orthoclase of unusual habit (Fig. 528). Adularia contains little, if any, soda (see analysis, p. 385).

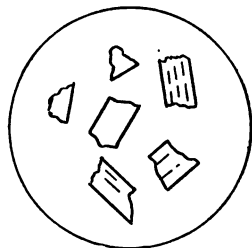


FIG. 532.

Orthoclase fragments.

6. In veins. Vein orthoclase has the same habit as adularia, but is not always transparent. Lindgren uses the name valencianite for it. Guanajuato, Mexico.

7. In granite-pegmatites, often in very large crystals.

8. In arkoses or feldspathic sandstones (Portland, Connecticut) and in some beach sands (Pacific Grove, California).

### MICROCLINE, $\text{KAlSi}_3\text{O}_8$

**Form.** In form microcline is practically the same as orthoclase, but is triclinic with the angle  $(001:010) = 89^\circ 30'$  instead of  $90^\circ$ . The angles are very close to those of orthoclase.

**Cleavage.** In two directions practically at right angles ( $89^\circ 30'$ ).

**H.** = 6.

**Sp. gr.**  $\pm 2.56$ .

**Color,** white, gray, reddish, green. The green variety is called amazon-stone.

**Optical Properties.**  $n_\gamma(1.529) - n_\alpha(1.522) = 0.007$ . Fragments are plates with middle first interference colors and are distinguished from orthoclase by the "gridiron" structure caused by polysynthetic twinning in two directions at right angles.

**Chemical Composition.** The same as for orthoclase.

**Blowpipe Tests.** The same as for orthoclase.

**Occurrence.** 1. In granite-pegmatites (near Florissant, Colorado).

2. In granites (but not in rhyolites).

3. In gneisses.

### PLAGIOCLASE GROUP—TRICLINIC

This is perhaps the best defined isomorphous group to be found among minerals. There is a perfect gradation in properties from the albite end of the group with the formula  $\text{NaAlSi}_3\text{O}_8$  to the anorthite end of the group with the formula  $\text{CaAl}_2\text{Si}_2\text{O}_8$ . Intermediate members of the group are designated by  $\text{Ab}_m\text{An}_n$ ,

Ab meaning the albite molecule and An the anorthite molecule. Crystals are triclinic, but with angles near those of orthoclase. The angle  $(001:010)$ , for example, varies from  $86^{\circ} 24'$  for albite to  $85^{\circ} 50'$  for anorthite, while for orthoclase the corresponding angle is  $90^{\circ} 0'$ . The plagioclases have good cleavage parallel to  $\{001\}$ , and imperfect cleavage parallel to  $\{010\}$ . Twinning is rarely absent in the plagioclases. The most common twinning is known as albite twinning, in which  $\{010\}$  is the twin-plane. This is usually polysynthetic and the twin striations show best on the  $\{001\}$  cleavage face and are *always* parallel to the  $(001:010)$  edge (Fig. 534). In pericline twinning, which is also polysynthetic, the  $b$ -axis is the twin-axis. This kind of twinning shows

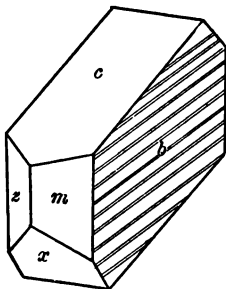


FIG. 533.—Pericline twinning.

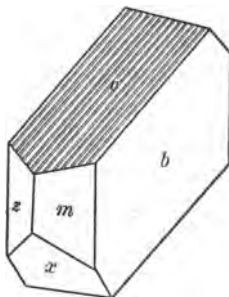


FIG. 534.—Albite twinning.

best on the  $\{010\}$  cleavage (Fig. 533), and the angle the striations make with  $(001:010)$  edge differs for the various plagioclases. This angle is given in the column of the following tabulation labelled angle of rhombic section. In optical properties the plagioclases are similar. They are all biaxial with  $2V$  varying from  $77^{\circ}$  to  $90^{\circ}$ . The indices of refraction vary from 1.54 for albite to 1.58 for anorthite. The double refraction is weak (0.007 to 0.012). Typical analyses are given on page 385. The following tabulation illustrates the continuous variation in properties.

		$n_\gamma$	$n_\alpha$	Extinction on 001	Extinction on 010	Angle of rhombic section	Sp. gr.	(001:010)
Albite .....	Ab	1.540	1.531	$4\frac{1}{2}^\circ$	$19^\circ$	$+22^\circ$	2.62	
	Ab <sub>2</sub> An <sub>1</sub>	1.543	1.534	3	12	$+10$	2.64	$86^\circ 24'$
Oligoclase .....	Ab <sub>2</sub> An <sub>1</sub>	1.549	1.542	1	$4\frac{1}{2}$	$+3$	2.66	$86^\circ 32'$
Andesine .....	Ab <sub>1</sub> An <sub>1</sub>	1.562	1.555	5	16	$-1$	2.69	$86^\circ 14'$
Labradorite .....	Ab <sub>1</sub> An <sub>2</sub>	1.577	1.567	18	$29\frac{1}{2}$	$-9$	2.73	$86^\circ 12'$
Bytownite .....	Ab <sub>1</sub> An <sub>2</sub>	1.584	1.572	$27\frac{1}{2}$	$33\frac{1}{2}$	$-10$	2.74	
Anorthite. ....	An	1.588	1.576	37	36	$-16$	2.76	$85^\circ 50'$

### ALBITE, NaAlSi<sub>3</sub>O<sub>8</sub>

**Form.** Albite occurs in small crystals, in lamellar masses, and intergrown with orthoclase or microcline. The crystals are triclinic, pinacoidal class, and are usually tabular parallel to {010}. The usual forms are the same as for orthoclase. Fig. 534 represents the common type of crystal with  $c\{001\}$ ,  $b\{010\}$ ,  $m\{110\}$ ,  $z\{1\bar{1}0\}$  and  $x\{1\bar{0}1\}$ . Albite, pericline, and Carlsbad twins are all common and sometimes two or more of these are combined on one crystal.

**Cleavage**, perfect parallel to {001} and less perfect parallel to {010}.

**H.** = 6.

**Sp. gr.**  $\pm 2.62$ .

**Color**, white, colorless or gray.

**Optical Properties.**  $n_\gamma(1.540) - n_\alpha(1.532) = 0.008$ . Fragments are plates with middle first order interference colors and extinction angles of about  $4^\circ(001)$  and about  $20^\circ(010)$ . The index of refraction is less than that of oil of cloves.

**Chemical Composition.** Sodium aluminum trisilicate, NaAlSi<sub>3</sub>O<sub>8</sub>; (Na<sub>2</sub>O = 11.8, Al<sub>2</sub>O<sub>3</sub> = 19.5, SiO<sub>2</sub> = 68.7). A little calcium is present for albite grades into oligoclase.

**Blowpipe Tests.** Fusible (4) to a colorless glass coloring the flame yellow.

Insoluble in ordinary acids.

**Occurrence.** 1. In granite-pegmatites associated with tourmaline, lepidolite, spodumene, etc.

2. In veins and seams, especially in the metamorphic rocks.

3. In certain soda-rich igneous rocks, usually intergrown with orthoclase or microcline. This intergrowth is known as *perthite*.

### OLIGOCLASE, $Ab_6An_1$ to $Ab_3An_1$

**Form.** Oligoclase occurs in cleavable masses and disseminated through rock masses, but is rarely found in distinct crystals.

**Cleavage,** perfect parallel to  $\{001\}$ , less perfect parallel to  $\{010\}$ .

**H.** = 6.

**Sp. gr.**  $\pm 2.65$ .

**Color,** white, colorless, greenish or reddish.

**Optical Properties.**  $n_r(1.547) - n_a(1.539) = 0.008$ . Fragments are plates with middle first order interference colors and extinction angles of about  $2^\circ(001)$  and about  $8^\circ(010)$ . The fragments usually show polysynthetic twinning.

**Chemical Composition.** Sodium-calcium aluminum silicate,  $Ab_6An_1$  to  $Ab_3An_1$ ; ( $Na_2O = 10.0$  to  $8.7$  per cent.;  $CaO = 3.0$  to  $5.3$  per cent.).

**Blowpipe Tests.** Fusible at 4.

Insoluble in ordinary acids.

**Occurrence.** 1. In acid and intermediate igneous rocks, such as the granite-rhyolite series and the diorite-andesite series. Strange to say, oligoclase is more common in granites than albite.

### LABRADORITE, $Ab_1An_1$ to $Ab_1An_3$

**Form.** Labradorite occurs in embedded crystals and in cleavable masses, but very rarely in distinct loose crystals. Albite twinning is the common kind of twinning.

**Cleavage,** perfect parallel to  $\{001\}$ , less perfect parallel to  $\{010\}$ .

**H.** = 6.

**Sp. gr.**  $\pm 2.71$ .

**Color,** gray or white, often showing a play of colors which is an optical effect due to minute inclusions.

**Optical Properties.**  $n_r(1.570) - n_a(1.561) = 0.009$ . Fragments are plates with middle first order interference colors and extinction angles of about  $12^\circ(001)$  and about  $20^\circ(010)$ . The fragments usually show polysynthetic twinning and often minute inclusions arranged in rows.

**Chemical Composition.** Calcium-sodium aluminum silicate,  $Ab_1An_1$  to  $Ab_1An_3$ ; (CaO = 10.4 to 15.3 per cent.;  $Na_2O = 2.8$  to 5.7 per cent.).

**Blowpipe Tests.** Fusible at 4.

Soluble with difficulty in HCl.

**Uses.** Labradorite rock is used as an ornamental stone.

**Occurrence.** 1. In basic igneous rocks such as gabbros, diabases, and basalts, associated with olivine, augite, hypersthene, ilmenite, and magnetite.

2. As the principal constituent of anorthosite, a basic plutonic igneous rock composed practically of labradorite. Adirondack Mts., New York State.

## B. METASILICATES

	LEUCITE,	$KAl(SiO_3)_2$
	ENSTATITE,	$MgSiO_3$
	Hypersthene,	$(Mg,Fe)SiO_3$
	DIOPSIDE,	$Ca(Mg,Fe)(SiO_3)_2$
Pyroxene Group	AUGITE,	$mCaMg(SiO_3)_2 + n(Mg,Fe)(Al,Fe)_2SiO_3$
	Aegirite,	$NaFe(SiO_3)_2$
	Spodumene,	$LiAl(SiO_3)_2$
	Wollastonite,	$CaSiO_3$
	Pectolite,	$HNaCa_2(SiO_3)_2$
	RHODONITE,	$MnSiO_3$
Amphibole Group	TREMOLITE,	$Ca(Mg,Fe)_3(SiO_3)_4$
	ACTINOLITE,	
	HÖRNBLENDE,	$mCa(Mg,Fe)_3(SiO_3)_2 + n(Al,Fe)(F,OH)SiO_3$
	Glaucophane,	$NaAl(SiO_3)_2 \cdot (Fe,Mg)SiO_3$

BERYL,  
CALAMINE,  
TALC,  
Pyrophyllite,  
ILMENITE,

$\text{Be}_3\text{Al}_2(\text{SiO}_3)_6$   
 $\text{Zn}_2(\text{OH})_2\text{SiO}_3$   
 $\text{H}_2\text{Mg}_3(\text{SiO}_3)_4$   
 $\text{HAl}(\text{SiO}_3)_2$   
 $\text{FeTiO}_3$

### LEUCITE, $\text{KAl}(\text{SiO}_3)_2$

**Form.** For leucite the characteristic form is well-defined embedded crystals. The crystals are isometric, the only common form being the trapezohedron {211} (Fig. 535). Cross-sections are eight-sided (Fig. 536).

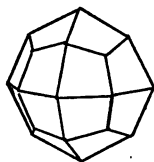


FIG. 535.

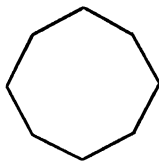


FIG. 536.

**H.** =  $5\frac{1}{2}$  to 6.

**Sp. gr.**  $\pm 2.5$ .

**Color,** white or gray.

**Optical Properties.**  $n = 1.50$ . Isotropic. Fragments are irregular and are either dark between crossed nicols or have very low first order interference colors.

**Chemical Composition.** Potassium aluminum metasilicate,  $\text{KAl}(\text{SiO}_3)_2$ . A little sodium is sometimes present.

**Blowpipe Tests.** Infusible.

Decomposed by HCl.

**Occurrence.** 1. In certain basic volcanic rocks in which leucite takes the place of the feldspars. Leucite is rare in the United States, but is especially common in central Italy.

### PYROXENE GROUP

The minerals listed under metasilicates from enstatite to rhodnite inclusive constitute a mineral group, though they are not



strictly isomorphous, for enstatite and hypersthene are orthorhombic and rhodonite is triclinic, while the others are monoclinic.

Typical analyses of the more important pyroxenes are given in the following tabulation.

Analyses of Pyroxenes

	MgO	FeO	CaO	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Misc.
Enstatite .....	36.9	3.2	.....	1.3	.....	58.0	ign. = 0.8
Bronzite .....	29.7	10.1	.....	1.3	.....	58.0	MnO = 1.0
Hypersthene ..	21.3	21.3	3.1	0.4	.....	51.4	
Diopside .....	17.3	1.9	25.0	0.5	1.0	54.3	
Diopside .....	16.1	5.0	24.9	1.5	0.6	52.8	
Diopside .....	10.0	12.3	22.1	2.0	1.3	51.1	MnO = 0.1; ign. = 0.3
Diallage .....	16.4	8.4	20.3	3.8	.....	50.2	
Augite .....	16.0	4.1	19.0	9.8	4.5	46.9	
Augite .....	7.6	9.4	12.3	21.5	3.8	42.2	Na <sub>2</sub> O = 3.0
Augite .....	13.2	4.3	21.3	8.2	3.7	46.5	TiO <sub>2</sub> = 2.8
Aegirite .....	0.3	9.5	2.0	1.8	23.3	51.4	Na <sub>2</sub> O = 11.9; TiO <sub>2</sub> = 0.1

### ENSTATITE, MgSiO<sub>3</sub>

**Form.** Enstatite usually occurs in lamellar or fibrous-lamellar masses. The mineral is orthorhombic, but distinct crystals are very rare.

**Cleavage,** distinct in several directions.

**H.** = 5½ to 6.

**Sp. gr.** ± 3.3.

**Color,** bronze, gray, or brown. **Luster,** metalloidal.

**Optical Properties.**  $n_r(1.67) - n_a(1.66) = 0.01$ . Fragments are prismatic with parallel extinction, low first order interference colors, and positive elongation.

**Chemical Composition.** Magnesium metasilicate; (MgO = 40.0 per cent.). Ferrous iron usually replaces part of the magnesium. Ferriferous enstatite is called *bronzite*.

**Blowpipe Tests.** Fusible on thin edges (6).

Insoluble in acids.

**Occurrence.** 1. In basic igneous rocks such as peridotites and gabbros.

2. In meteorites.

### Hypersthene, (Fe,Mg)SiO<sub>3</sub>

**Form.** Hypersthene usually occurs in cleavable masses or disseminated through rock masses.

**Cleavage,** good cleavage in one direction.

**H.** = 5½.

**Sp. gr.** ± 3.4.

**Color,** dark brown or greenish brown.

**Optical Properties.**  $n_\gamma(1.70) - n_\alpha(1.69) = 0.01$ . Fragments are prismatic with parallel extinction, bright interference colors, and positive elongation. Hypersthene is usually pleochroic, changing from pink to green.

**Chemical Composition.** Ferrous-magnesium metasilicate, (Fe,Mg)SiO<sub>3</sub>.

**Blowpipe Tests.** Fusible (5) to a black glass. On charcoal in R.F. becomes magnetic.

Soluble with difficulty in HCl.

**Occurrence.** 1. In basic igneous rocks especially gabbros and norites.

### DIOPSIDE, Ca(Mg,Fe)(SiO<sub>3</sub>)<sub>2</sub>

**Form.** In crystals, granular masses, disseminated through rocks, but rarely fibrous or columnar.

Monoclinic system, prismatic class.  $a:b:c = 1.092:1:0.589$ ;  $\beta = 74^\circ 10'$ . Usual forms:  $a\{100\}$ ,  $b\{010\}$ ,  $m\{110\}$ ,  $c\{001\}$ ,  $p\{111\}$ ,  $o\{\bar{2}21\}$ ,  $d\{\bar{3}11\}$ ,  $d\{\bar{1}01\}$ . Interfacial angles:  $mm(110:1\bar{1}0) = 92^\circ 50'$ ;  $pp(111:1\bar{1}1) = 48^\circ 29'$ ;  $oo(\bar{2}21:\bar{2}\bar{2}1) = 84^\circ 11'$ .

The habit is usually prismatic in the direction of the  $c$ -axis. Figs. 537 to 540 represent typical crystals. The cross-section of crystals is characteristic, usually being four- or eight-sided as represented in Fig. 541.

**Cleavage**, imperfect in two directions at angles of  $87^{\circ} 10'$  and  $92^{\circ} 50'$  (parallel to the unit prism  $\{110\}$ ). There is often parting parallel to  $\{001\}$  which is more prominent than the cleavage. The variety *diallage* has well-defined parting parallel to  $\{100\}$ .

**H.** = 4 to 6.

**Sp. gr.**  $\pm 3.2$ .

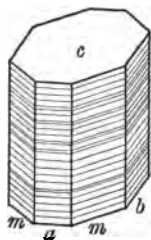


FIG. 537.

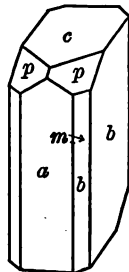


FIG. 538.

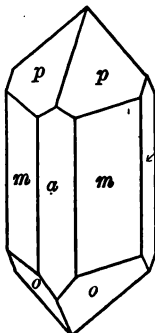


FIG. 539.

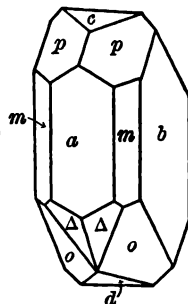


FIG. 540.

**Color**, white, gray, and various tints of green.

**Optical Properties.**  $n_r(1.70) - n_a(1.67) = 0.03$ . Fragments are prismatic and colorless or pale green with bright interference colors and an extinction angle of  $20^{\circ}$ – $30^{\circ}$ . A thin parting parallel to  $\{001\}$  gives an interference figure consisting of an

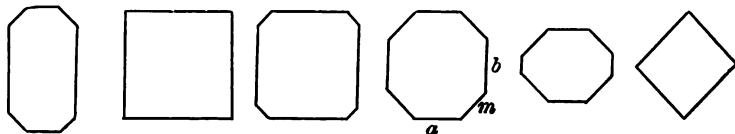


FIG. 541.—Cross-sections of diopside and augite.

axial bar with concentric rings. Diallage has parallel extinction and positive elongation.

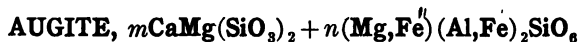
**Chemical Composition.** Calcium magnesium-ferrous metasilicate varying from  $\text{CaMg}(\text{SiO}_3)_2$  to  $\text{CaFe}(\text{SiO}_3)_2$ . It may also contain small amounts of aluminum, ferric iron, and manganese.

**Blowpipe Tests.** Fusible at 4 to a colorless or pale green glass. Insoluble in acids.

**Occurrence.** 1. In crystalline limestones as a contact mineral associated with garnet.

2. In schists and other metamorphic rocks, both in the rock mass and in seams.

3. In gabbros and peridotites (the variety diallage).



**Form.** Augite usually occurs in embedded crystals. The crystals are monoclinic, prismatic class, with the forms:  $a\{100\}$ ,  $b\{010\}$ ,  $m\{110\}$ ,  $s\{\bar{1}11\}$ . Interfacial angles:  $mm(110:1\bar{1}0) = 92^\circ 50'$ ,  $ss(\bar{1}11:\bar{1}\bar{1}1) = 59^\circ 11'$ . The habit is usually prismatic (Figs. 542–4) and either square or octagonal in outline (see Fig. 541). Twins with  $a\{100\}$  as twin-plane are common (Fig. 545).

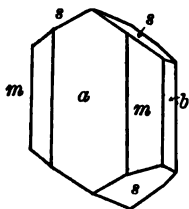


FIG. 542.

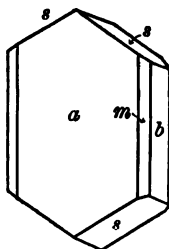


FIG. 543.

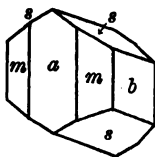


FIG. 544.

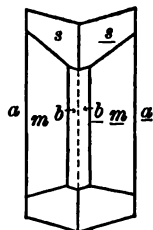


FIG. 545.

**Cleavage**, imperfect in two directions parallel to  $\{110\}$ , and at angles of  $92^\circ 50'$  and  $87^\circ 10'$ .

$H. = 5\frac{1}{2}$ .

**Sp. gr.**  $\pm 3.3$ .

**Color**, dark green to black.

**Optical Properties.**  $n_r(1.73) - n_a(1.71) = 0.02$ . Fragments are prismatic with bright interference colors and large extinction angles ( $25^\circ$  to  $40^\circ$ ). In thin fragments it is only slightly pleochroic, if at all. This usually distinguishes augite from hornblende.

**Chemical Composition.** An isomorphous mixture of  $\text{CaMg}(\text{SiO}_3)_2$  and  $(\text{Mg,Fe})(\text{Al,Fe})_2\text{SiO}_6$  in varying proportions. The presence of aluminum and ferric iron distinguishes augite from diopside. Sodium and titanium are sometimes present.

**Blowpipe Tests.** Fusible at 4 to a black glass.

Insoluble in acids.

**Occurrence.** 1. In basic igneous rocks, especially basalts and diabases, often as phenocrysts. Bohemia.

### Aegirite, $\text{NaFe}(\text{SiO}_3)_2$

**Form.** In crystal form aegirite is like augite, but is more apt to occur in long prismatic or acicular crystals.

**Cleavage,** imperfect prismatic in two directions at angles of  $93^\circ$  and  $87^\circ$ .

**H.** = 6.

**Sp. gr.**  $\pm 3.5$ .

**Color,** black in thick crystals, in thin crystals green.

**Optical Properties.**  $n_p = 1.75$ . Fragments are prismatic and green in color. The interference colors are bright and the extinction practically parallel. The pleochroism from yellowish-green to bright green is a prominent feature.

**Chemical Composition.** Sodium ferric metasilicate,  $\text{NaFe}(\text{SiO}_3)_2$ . Analyses also show ferrous iron.

**Blowpipe Tests.** Fusible (3) to a black slightly magnetic globule, coloring the flame yellow.

Only slightly soluble in HCl.

**Occurrence.** 1. In soda-rich igneous rocks such as nepheline-syenites, phonolites, soda-syenites, and soda-granites. Magnet Cove, Arkansas.

### Spodumene, $\text{LiAl}(\text{SiO}_3)_2$

**Form.** Spodumene occurs in rough monoclinic crystals and in cleavable masses. The habit of the crystals is prismatic and usually tabular parallel to  $\{100\}$ .

**Cleavage**, in two directions at angles of  $93^\circ$  and  $87^\circ$ . There is also, at times, parting parallel to {100} which causes the mineral to break into plates.

**H.** =  $6\frac{1}{2}$ .

**Sp. gr.**  $\pm 3.1$ .

**Color**, white, gray, colorless, lilac, greenish.

**Optical Properties.**  $n_r(1.67) - n_a(1.65) = 0.02$ . Fragments are prismatic with first order interference colors and oblique extinction of  $20^\circ$  to  $25^\circ$ .

**Chemical Composition.** Lithium aluminum metasilicate,  $\text{LiAl}(\text{SiO}_3)_2$ .

**Blowpipe Tests.** Fuses at 3.5 to a clear glass giving a purple-red flame.

Insoluble in acids.

**Uses.** Spodumene has been used to some extent as a source of lithium salts. A transparent lilac variety called *kunzite* is used as a gem.

**Occurrence.** 1. In granite-pegmatites associated with albite, lepidolite, tourmaline, etc. Pennington County, South Dakota. One crystal from the Etta Mine in this county measured thirty feet in length.

### WOLLASTONITE, $\text{CaSiO}_3$

**Form.** Wollastonite is found in cleavable, columnar, fibrous, and compact masses. Distinct crystals are rare. They are monoclinic and are elongate in the direction of the *b*-axis.

**Cleavage**, in two directions (001 and 100) at angles of  $84\frac{1}{2}^\circ$ .

**H.** =  $4\frac{1}{2}$  to 5.

**Sp. gr.**  $\pm 2.9$ .

**Color**, white or gray.

**Optical Properties.**  $n_r(1.63) - n_a(1.62) = 0.01$ . Fragments are acicular with parallel extinction and positive elongation. The interference colors are bright.

**Chemical Composition.** Calcium metasilicate,  $\text{CaSiO}_3$ .

**Blowpipe Tests.** Fuses at 4 to a white glass giving a yellowish-red flame.

*Soluble!*

^Gelatinizes with HCl, and usually effervesces because of admixed calcite.

**Occurrence.** 1. In crystalline limestones at the contact with igneous rocks and often associated with garnet, diopside, etc.

### **Pectolite, $\text{HNaCa}_2(\text{SiO}_3)_3$**

**Form.** Pectolite occurs in acicular crystals, in fibrous radiating forms, and in compact masses. Crystals are monoclinic, but usually are very minute.

**H.** =  $4\frac{1}{2}$ .

**Sp. gr.**  $\pm 2.7$ .

**Color,** white.

**Optical Properties.**  $n_r(1.63) - n_a(1.60) = 0.03$ . Fragments are acicular with bright interference colors, parallel extinction, and positive elongation.

**Chemical Composition.** Acid sodium calcium metasilicate  $\text{HNaCa}_2(\text{SiO}_3)_3$  or  $\text{H}_2\text{SiO}_3 \cdot \text{Na}_2\text{SiO}_3 \cdot 4\text{Ca}(\text{SiO})_3$ ; ( $\text{H}_2\text{O} = 2.7$  per cent.).

**Blowpipe Tests.** Easily fusible ( $2\frac{1}{2}$ ) giving a yellow flame. In the closed tube gives a little water.

Decomposed by HCl with the separation of silica.

**Occurrence.** 1. A secondary mineral in cavities of basalts and diabases associated with calcite, zeolites, prehnite, and datolite. Bergen Hill, New Jersey.

### **RHODONITE, $\text{MnSiO}_3$**

**Form.** Rhodonite is found in cleavable and compact masses and occasionally in crystals. The crystals are triclinic, but similar to diopside and augite in angles.

**Cleavage,** in two directions at angles of  $92\frac{1}{2}^\circ$  (parallel to 100) and also an additional parting parallel to (100) the angle (100:110) being  $48^\circ 33'$ .

**H.** = 6.

**Sp. gr.**  $\pm 3.6$ .

**Color,** pink or red, often stained black by manganese oxids.

**Optical Properties.**  $n_g(1.74) - n_a(1.72) = 0.02$ . Fragments are prismatic with bright interference colors and large extinction angles (20 to 25°).

**Chemical Composition.** Manganese metasilicate,  $\text{MnSiO}_3$ . Calcium is usually present and sometimes iron.

**Blowpipe Tests.** Fusible at 3 to a dark glass.

Partially soluble in HCl.

**Uses.** Compact rhodonite is used as an ornamental stone, especially in Russia.

**Occurrence.** 1. In veins.

2. In crystalline limestones with willemite, franklinite, and zincite. Franklin Furnace, New Jersey.

## AMPHIBOLE GROUP

The amphibole group is parallel to the pyroxene group, but the orthorhombic and triclinic members are so rare that no account of them will be given here. The amphiboles differ from the pyroxenes mainly in the prism and cleavage angle, which is 56° instead of 87°. For many of the pyroxenes there are corresponding amphiboles, but they cannot be regarded as dimorphous minerals. For example, diopside is  $\text{CaMg}(\text{SiO}_3)_2$ , while the corresponding tremolite is  $\text{CaMg}_3(\text{SiO}_3)_4$ . Tremolite-actinolite and hornblende contain a small amount of water of constitution, while diopside and augite, if unaltered, contain none. The following analyses (except glaucophane) were made by Stanley in order to determine the chemical constitution of the amphiboles.

Analyses of Amphiboles

	CaO	MgO	FeO	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	TiO <sub>2</sub>	H <sub>2</sub> O	Na <sub>2</sub> O	K <sub>2</sub> O	F
Tremolite . . . . .	13.2	24.1	0.6	1.8	.....	57.7	0.1	1.6	0.5	0.2	0.4
Actinolite . . . . .	12.1	21.2	5.5	1.2	0.8	56.3	.....	1.8	0.2	0.3	0.1
Hornblende . . . . .	9.8	12.6	10.5	8.3	6.9	43.8	0.8	0.6	3.4	1.3	1.8
Hornblende . . . . .	11.5	11.2	14.3	11.6	2.7	42.0	1.5	0.6	2.5	0.1	0.8
Hornblende . . . . .	12.0	14.2	2.2	17.6	7.2	39.9	1.7	0.4	3.2	0.2	0.1
Glaucophane . . . . .	2.0	10.3	9.8	9.3	4.4	54.5	0.4	1.8	7.6	0.2	....



**TREMOLITE-ACTINOLITE,  $\text{Ca}(\text{Mg,Fe})_3(\text{SiO}_3)_4$** 

**Form.** Tremolite and actinolite occur in long prismatic crystals and in columnar and fibrous aggregates. Crystals are monoclinic with the prism  $\{110\}$  and the pinacoid  $\{010\}$ , but rarely have terminal faces. The axial ratios and interfacial angles are like those of hornblende. Characteristic cross-sections are shown in Fig. 546.

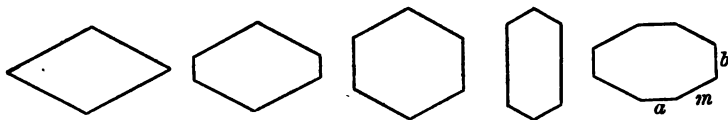


FIG. 546.—Cross sections of tremolite, actinolite, and hornblende.

**Cleavage**, in two directions at angles of  $56^\circ$  and  $124^\circ$  parallel to  $\{110\}$ . The cleavage is more perfect than that of diopside.

**H.** =  $5\frac{1}{2}$ .

**Sp. gr.**  $\pm 3.0$ .

**Color**, white or gray (tremolite); pale green to dark green (actinolite).

**Optical Properties.**  $n_r(1.636) - n_a(1.611) = 0.025$ . Fragments are prismatic or acicular with bright interference colors, positive elongation, and extinction angles of  $10^\circ$  to  $15^\circ$ .

**Chemical Composition.** Calcium magnesium-iron metasilicate  $\text{Ca}(\text{Mg,Fe})_3(\text{SiO}_3)_4$ . Tremolite has very little, if any, iron, while actinolite runs as high as 6 per cent. in  $\text{FeO}$ . Aluminum and ferric iron are very low and this is the principal chemical distinction between these minerals and hornblende.

**Blowpipe Tests.** Fusible at 4 to a glass.

Insoluble in acids.

**Uses.** The fibrous tremolite is one kind of asbestos.

**Occurrence.** 1. Tremolite occurs especially in crystalline dolomitic limestones. Lee, Massachusetts.

2. Actinolite occurs especially in schists often associated with talc.

**HORNBLENDE**,  $m\text{Ca}(\text{Mg},\text{Fe})_3(\text{SiO}_3)_4 + n(\text{Al},\text{Fe})(\text{F},\text{OH})\text{SiO}_3$

**Form.** Hornblende occurs in well-defined crystals, in cleavages, in disseminated crystals and grains, and in bladed aggregates.

Monoclinic system. Prismatic class. Axial ratio:  $a:b:c = 0.551:1:0.293$ ;  $\beta = 73^\circ 58'$ . Usual forms:  $m\{110\}$ ,  $b\{010\}$ ,  $a\{100\}$ ,  $r\{011\}$ ,  $p\{\bar{1}01\}$ . Interfacial angles:  $mm(110:\bar{1}\bar{1}0) = 55^\circ 49'$ ,  $rr\{011:0\bar{1}1\} = 31^\circ 32'$ ,  $rp\{011:\bar{1}01\} = 34^\circ 25'$ . Habit short to long prismatic, usually pseudohexagonal or rhombic in cross-section. (See Fig. 546.) The common type of hornblende crystal is that of Fig. 547.

**Cleavage**, perfect in two directions at angles of  $56^\circ$  and  $124^\circ$ , parallel to  $\{110\}$ .

**H.** =  $5\frac{1}{2}$ .

**Sp. gr.**  $\pm 3.2$ .

**Color**, dark green, dark brown, or black.

**Optical Properties.**  $n_\gamma(1.653) - n_\alpha(1.629) = 0.024$ . Fragments are prismatic and green or brown in color. The extinction angle varies from  $5^\circ$  to  $20^\circ$  and the elongation is positive. Pleochroism is a marked feature of hornblende. The colors vary from pale to deep green, from yellowish-green to bluish-green, from brown to greenish-brown, or from pale to deep brown. By the pleochroism and the extinction hornblende may easily be distinguished from augite, which it often greatly resembles.

**Chemical Composition.** A complex metasilicate of calcium, magnesium, ferrous iron, aluminum, and ferric iron with fluorine and hydroxyl. The formula given above was established by Penfield and Stanley (see analyses, page 401).

**Blowpipe Tests.** Fusible at 4 to a black glass.

Insoluble in acids.

**Occurrence.** 1. In volcanic igneous rocks such as andesites and certain basalts.

2. In plutonic igneous rocks especially granites, syenites, and diorites, rarely in gabbros and peridotites.

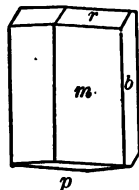


FIG. 547.

3. In diabases and gabbros as an alteration product of augite. This alteration product is called *uralite* and the process is known as uralitization.

4. In schists and gneisses often forming rock masses, the hornblende schists and amphibolites.

### Glaucophane, $\text{NaAl}(\text{SiO}_3)_2 \cdot (\text{Fe}, \text{Mg})\text{SiO}_3$

**Form.** Glaucophane occurs in small disseminated crystals and in fibrous masses. Crystals are prismatic in habit with  $\{100\}$ ,  $\{010\}$ , and  $\{110\}$ , but are rarely terminated. The cross-section as seen in thin rock sections is pseudo-hexagonal or rhombic (Fig. 546).

**Cleavage**, parallel to  $\{110\}$ , *i.e.*, in two directions at angles of  $56^\circ$  and  $124^\circ$ .

**H.** = 6.

**Sp. gr.**  $\pm 3.1$ .

**Optical Properties.**  $n_r(1.64) - n_a(1.62) = 0.02$ . Fragments are prismatic and blue in color with pleochroism from blue to violet. The extinction is practically parallel and the elongation positive.

**Chemical Composition.** Sodium aluminum, iron-magnesium metasilicate,  $\text{NaAl}(\text{SiO}_3)_2 \cdot (\text{Fe}, \text{Mg})\text{SiO}_3$ . Glaucophane is one of the group known as soda amphiboles.

**Blowpipe Tests.** Easily fusible (3) to a dark glass giving an intense yellow flame.

Insoluble in acids.

**Occurrence.** 1. In schists and gneisses often constituting the main part of the rock. Glaucophane schists and glaucophane gneisses are especially abundant in the Coast Ranges of California.

### BERYL, $\text{Be}_3\text{Al}_2(\text{SiO}_3)_6$

**Form.** For beryl the characteristic forms are crystals and columnar masses. Beryl crystallizes in the hexagonal system, and is one of the few examples of the dihexagonal bipyramidal classes. Axial ratio:  $c = 0.498$ . Usual forms:  $c\{0001\}$ ,  $m\{10\bar{1}0\}$ ,

$a\{11\bar{2}0\}$ ,  $p\{10\bar{1}1\}$ ,  $s\{11\bar{2}1\}$ . Interfacial angles:  $cp(0001:10\bar{1}1) = 29^\circ 56\frac{1}{2}'$ ;  $cs\{0001:11\bar{2}1\} = 44^\circ 56'$ ;  $ma(10\bar{1}0:11\bar{2}0) = 30^\circ 0'$ . The habit is usually prismatic (Figs. 548–550), but sometimes tabular (Fig. 551). Crystals are often very large.

**H.** =  $7\frac{1}{2}$  to 8.

**Sp. gr.**  $\pm 2.7$ .

**Color**, usually various tints of green, but sometimes white, yellow, pink, or blue.

**Optical Properties.**  $n_\gamma(1.570) - n_\alpha(1.564) = 0.006$ . Fragments are irregular with low first order interference colors.

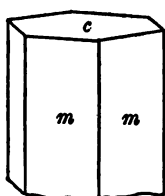


FIG. 548.

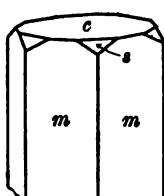


FIG. 549.

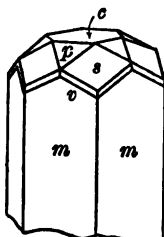


FIG. 550.

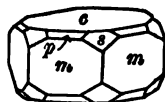


FIG. 551.

**Chemical Composition.** Beryllium aluminum metasilicate,  $\text{Be}_3\text{Al}_2(\text{SiO}_3)_6$ . The alkalis, sodium, lithium, and caesium often partly replace beryllium.

**Blowpipe Tests.** Fusible on thin edges (6). Insoluble in acids.

**Uses.** The deep green variety, emerald, is a valuable gem. A sea-green variety called aquamarine and a yellow variety called golden beryl are also gems.

**Occurrence.** 1. In granite-pegmatites associated with topaz, albite, lepidolite, etc. San Diego County, California.

2. In mica-schists and gneisses, North Carolina.

### CALAMINE, $\text{Zn}_2(\text{OH})_2\text{SiO}_3$

**Form.** Calamine occurs as drusy crystalline coatings, more rarely in botryoidal and stalactitic forms and also massive. Crystals are orthorhombic, pyramidal class. The habit is usually

tabular parallel to  $\{010\}$  and the two ends of the crystal are differently terminated. Fig. 552 is a typical crystal with the forms  $c\{001\}$ ,  $b\{010\}$ ,  $m\{110\}$ ,  $i\{031\}$ ,  $t\{301\}$ ,  $e\{01\bar{1}\}$ ,  $v\{12\bar{1}\}$ .

**H.** = 5.

**Sp. gr.**  $\pm 3.4$ .

**Color**, colorless, white, and pale colors.

**Optical Properties.**  $n_r(1.64) - n_a(1.61) = 0.03$ . Fragments are irregular and prismatic with parallel extinction. Crystals have parallel extinction and positive elongation. The interference colors are bright.

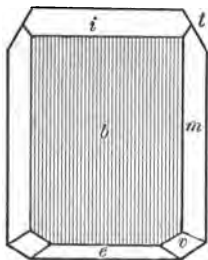
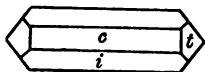


FIG. 552.

**Chemical Composition.** Basic zinc metasilicate,  $\text{Zn}_2(\text{OH})_2\text{SiO}_3$  or  $\text{ZnSiO}_3 \cdot \text{Zn}(\text{OH})_2$ ; (Zn = 54.2 per cent.,  $\text{H}_2\text{O}$  = 7.5 per cent.) The common impurities are iron and aluminum.

**Blowpipe Tests.** Fusible on the edges (5). In the closed tube decrepitates and gives off water. Heated with cobalt nitrate solution on charcoal, the assay becomes blue and the sublimate on the coal green.

Soluble in HCl, giving a fine jelly.

**Uses.** Calamine is one of the ores of zinc.

**Occurrence.** 1. A secondary mineral usually derived from sphalerite and often associated with smithsonite. It is found in the upper or oxidized zone of mines. Granby, Newton County, Missouri, is a prominent locality.

### TALC, $\text{H}_2\text{Mg}_3(\text{SiO}_4)_4$

**Form.** Talc is found in scales, in foliated, compact, or fibrous masses. Distinct crystals are exceedingly rare.

**Cleavage**, perfect in one direction.

**H.** = usually 1, but sometimes 4.

**Sp. gr.**  $\pm 2.7$ .

**Color**, white, gray, or pale green. Luster, pearly.

**Optical Properties.**  $n_r(1.59) - n_a(1.54) = 0.05$ . Cleavage flakes give a negative biaxial interference figure with a small axial angle ( $2E = 10^\circ - 20^\circ$ ).

**Chemical Composition.** Acid magnesium metasilicate,  $H_2Mg_3(SiO_4)_4$ ; ( $H_2O = 4.8$  per cent.). Talc usually contains Fe and Al in small quantities.

**Blowpipe Tests.** Fusible ( $5\frac{1}{2}$ ) on thin edges. In the closed tube gives water on intense ignition. When heated with cobalt nitrate solution intensely it gives a faint pink color.

Not decomposed by acids.

**Uses.** Talc is used for soap, French chalk, talcum powder, and in the form of soapstone as a refractory material. A fibrous variety is used in the manufacture of paper.

**Occurrence.** 1. A secondary mineral occurring as an alteration product of various silicates such as serpentine, enstatite, and actinolite.

2. In schists often forming the rock-masses known as talc-schists and soapstones.

### Pyrophyllite, $HA1(SiO_3)_2$

**Form.** In radiated forms and compact masses, but not in distinct crystals.

**H.** =  $1\frac{1}{2}$ .

**Sp. gr.**  $\pm 2.8$ .

**Color,** white, yellow, gray, brown. **Luster,** pearly.

**Optical Properties.**  $n_r(1.59) - n_a(1.57) = 0.02$ . Fragments are prismatic with parallel extinction and positive elongation. The interference colors are low first order.

**Chemical Composition.** Acid aluminum metasilicate,  $HA1(SiO_3)_2$ ; ( $H_2O = 5.0$  per cent.).

**Blowpipe Tests.** Infusible, but often exfoliates. In the closed tube gives water on intense ignition. Heated with cobalt nitrate solution it becomes deep blue. This test distinguishes pyrophyllite from talc.

Partially decomposed by  $H_2SO_4$ .

**Occurrence.** 1. In schistose metamorphic rocks.

**ILMENITE,  $\text{FeTiO}_3$ ,**

**Form.** Ilmenite occurs in tabular hexagonal crystals, in flat plates without definite outline, in disseminated grains, in compact masses, and in the form of sand. The crystals resemble those of hematite in habit and angles, but the crystal class is different, ilmenite belonging to the trigonal rhombohedral class.

**H.** = 5 to 6.

**Sp. gr.**  $\pm 4.7$ .

**Color,** black. **Luster,** submetallic or metallic. **Streak,** black to brownish-red. **Slightly magnetic.**

**Chemical Composition.** Ferrous metatitanate,  $\text{FeTiO}_3$ ; (Fe = 36.8 per cent.), analogous to a metasilicate. Ilmenite usually contains ferric iron and also magnesium. It grades on the one hand into hematite and on the other into  $\text{MgTiO}_3$ , a mineral called geikielite, as the following analyses show. Pyrophanite with the composition,  $\text{MnTiO}_3$ , and senaite with the composition,  $(\text{Fe}, \text{Mn}, \text{Pb})\text{TiO}_3$ , also belong to the ilmenite group.

**Analyses of Minerals of the Ilmenite Group**

	FeO	MgO	MnO	TiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	Misc.
Hematite .....	7.6	.....	0.4	9.1	83.4	
Ilmenite .....	22.4	0.5	0.3	23.7	53.7	
Ilmenite .....	36.5	0.6	2.7	45.9	14.3	
Picroilmenite .....	24.4	14.2	.....	56.1	5.4	
Geikielite .....	6.3	28.5	.....	63.8	1.9	
Pyrophanite .....	.....	.....	46.9	50.5	1.1	SiO <sub>2</sub> = 1.6
Senaite .....	27.0	0.3	10.4	52.1	.....	PbO = 10.9

**Blowpipe Tests.** Infusible. The soda fusion dissolved in HCl and boiled with metallic tin gives a violet solution.

Slowly soluble in HCl. Decomposed by fusion with  $\text{KHSO}_4$ .

**Occurrence.** 1. In igneous rocks, especially diabases.

2. As a magmatic segregation in igneous rocks.

3. As a prominent constituent of sands, especially the "black sands."

## C. ORTHOSILICATES

	NEPHELITE,	$\text{NaAlSiO}_4$
Sodalite Group.	{ Sodalite,	$\text{Na}_4\text{Al}_3\text{Cl}(\text{SiO}_4)_3$
	{ Lazurite,	$\text{Na}_6\text{Al}_3\text{S}(\text{SiO}_4)_3$
	GARNET,	$\text{R}^{\text{IV}}_3\text{R}^{\text{III}}_2(\text{SiO}_4)_3$
	OLIVINE,	$(\text{Mg}, \text{Fe})_2\text{SiO}_4$
	WILLEMITE,	$\text{Zn}_2\text{SiO}_4$
	WERNERITE,	$m\text{Ca}_4\text{Al}_4\text{Si}_6\text{O}_{25} + n\text{Na}_4\text{Al}_3\text{Si}_3\text{O}_{24}\text{Cl}$
	VESUVIANITE,	$\text{Ca}_3\text{Al}_2(\text{OH}, \text{F})(\text{SiO}_4)_3$
	ZIRCON,	$\text{ZrSiO}_4$
	TOPAZ,	$\text{Al}_2\text{F}_2\text{SiO}_4$
	Sillimanite,	$\text{Al}_2\text{OSiO}_4$
	ANDALUSITE,	$\text{Al}_2\text{OSiO}_4$
	CYANITE,	$\text{Al}_2\text{OSiO}_4$
	DATOLITE,	$\text{CaB}(\text{OH})\text{SiO}_4$
	Zoisite,	$\text{HCa}_2\text{Al}_2(\text{SiO}_4)_3$
	EPIDOTE,	$\text{Ca}_2(\text{Al}, \text{Fe})_2(\text{OH})(\text{SiO}_4)_3$
	Allanite,	$(\text{Ca}, \text{Fe})(\text{Al}, \text{Ce}, \text{Fe})_2(\text{OH})(\text{SiO}_4)_3$
	Axinite,	$\text{HCa}_2(\text{Fe}, \text{Mn})\text{Al}_2\text{B}(\text{SiO}_4)_4$
	PREHNITE,	$\text{H}_2\text{Al}_2\text{Ca}_2(\text{SiO}_4)_3$
	Chondrodite,	$\text{Mg}_5(\text{F}, \text{OH})_2(\text{SiO}_4)_2$
Mica Group	{ MUSCOVITE,	$\text{H}_2\text{KAl}_3(\text{SiO}_4)_3$
	{ LEPIDOLITE,	$\text{LiKAl}_2(\text{OH}, \text{F})(\text{SiO}_3)_3$
	{ BIOTITE,	$(\text{H}, \text{K})_2(\text{Mg}, \text{Fe})_2\text{Al}_2(\text{SiO}_4)_3$
	{ PHLOGOPITE,	$\text{H}_2\text{KMg}_3\text{Al}(\text{SiO}_4)_3$

NEPHELITE,  $\text{NaAlSiO}_4$ 

**Form.** Nephelite occurs in embedded crystals or grains and in massive forms. Crystals are hexagonal and short prismatic in habit. The cross-sections are six-sided and rectangular.

**H.** =  $5\frac{1}{2}$  to 6.

**Sp. gr.**  $\pm 2.6$ .

**Color,** white, gray, or reddish. **Luster,** greasy.

**Optical Properties.**  $n_\gamma(1.543) - n_\alpha(1.538) = 0.005$ . Fragments are irregular with low first order interference colors.

**Chemical Composition.** Essentially sodium aluminum orthosilicate,  $\text{NaAlSiO}_4$ , but a mixture of this compound with  $\text{KAlSiO}_4$  and  $\text{NaAlSi}_3\text{O}_8$ .



**Blowpipe Tests.** Fuses at 4 to a colorless glass.

Gelatinizes with HCl.

**Occurrence.** 1. In nephelite-syenites, phonolites, and other rare soda rich igneous rocks. It is often associated with orthoclase, but never with quartz. Magnet Cove, Arkansas.

### SODALITE GROUP—ISOMETRIC

Besides sodalite and lazurite, noselite  $\text{Na}_5\text{Al}_3(\text{SO}_4)(\text{SiO}_4)_3$  and haüynite  $\text{Na}_3\text{CaAl}_3(\text{SO}_4)(\text{SiO}_4)_3$  belong to this group.

#### Sodalite, $\text{Na}_4\text{Al}_3\text{Cl}(\text{SiO}_4)_3$

**Form.** Sodalite usually occurs in disseminated or massive forms, but rarely isometric dodecahedral crystals are found.

**Cleavage,** indistinct.

**H.** =  $5\frac{1}{2}$  to 6.

**Sp. gr.**  $\pm 2.3$ .

**Color,** blue, gray or colorless.

**Optical Properties.**  $n = 1.48$ . Isotropic. Fragments are irregular and colorless, but dark between crossed nicols.

**Chemical Composition.** Sodium aluminum chlorid-orthosilicate,  $\text{Na}_4\text{Al}_3\text{Cl}(\text{SiO}_4)_3$  or  $3\text{NaAlSiO}_4 \cdot \text{NaCl}$ .

**Blowpipe Tests.** Fusible with intumescence to a colorless glass. The  $\text{NaPO}_3$  bead with CuO gives an azure blue flame.

Gelatinizes with HCl.

**Occurrence.** 1. In soda-rich igneous rocks such as nepheline syenites and phonolites.

#### Lazurite, $\text{Na}_5\text{Al}_3\text{S}(\text{SiO}_4)_3$

**Form.** Lazurite usually occurs in compact massive form more or less mixed with calcite, pyrite, and other silicates. This mixture is known as *lapis lazuli*.

**H.** = 5 to  $5\frac{1}{2}$ .

**Sp. gr.**  $\pm 2.4$ .

**Color,** deep blue. Streak, blue.

**Optical Properties.**  $n$  about 1.5. Isotropic. Fragments are

irregular, deep blue, non-pleochroic, and dark between crossed nicols.

**Chemical Composition.** Sodium aluminum sulfid-orthosilicate,  $\text{Na}_3\text{Al}_3\text{S}(\text{SiO}_4)_3$  or  $3\text{NaAlSiO}_4 \cdot \text{Na}_2\text{S}$ . It usually contains calcium and the sulfate radical, due to isomorphous replacement.

**Blowpipe Tests.** Fuses (3) with intumescence to a white glass. Soluble in  $\text{HCl}$  with gelatinization and with the evolution of  $\text{H}_2\text{S}$ .

**Uses.** Lapis lazuli is a valuable ornamental stone. The paint called ultramarine was formerly lapis lazuli, but is now made artificially.

**Occurrence.** 1. As a contact mineral in crystalline limestones associated with diopside and other silicates. Eastern Asia is the principal locality.

### GARNET, $\text{R}_3^{\text{II}}\text{R}_2^{\text{III}}(\text{SiO}_4)_3$

**Form.** Garnet is found in distinct crystals, which are usually embedded, in granular or compact masses, and in the form of sand.

Garnet crystallizes in the hexoctahedral class of the isometric system. The usual forms are the dodecahedron  $d\{110\}$  and the

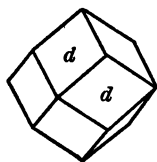


FIG. 553.

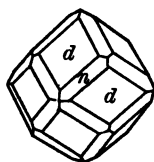


FIG. 554.

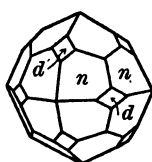


FIG. 555.

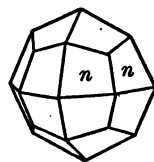


FIG. 556.

trapezohedron  $n\{211\}$ . The hexoctahedron  $\{321\}$  is sometimes found, but the cube and octahedron are exceedingly rare forms for garnet. Figs. 553-556 illustrate commonly occurring garnet crystals ranging from dodecahedral habit to trapezohedral habit. Interfacial angles:  $dd(110:101) = 60^\circ$ ;  $dd(110:\bar{1}\bar{1}0) = 90^\circ 0'$ ;  $nn(211:121) = 33^\circ 33\frac{1}{2}'$ ;  $nn(211:2\bar{1}1) = 48^\circ 11\frac{1}{2}'$ ;  $dn(110:211) = 30^\circ$ .

H. = 7.

Sp. gr. varies from 3.5 to 4.2.

Color, red, brown, yellow, green, black.

**Optical Properties.**  $n$  varies from 1.74 to 1.85. Isotropic. Fragments are irregular, colorless or pale red, and dark between crossed nicols. Some varieties have very weak double refraction.

**Chemical Composition.** Garnet is an isomorphous mixture of the following compounds:

Grossularite	$\text{Ca}_3\text{Al}_2(\text{SiO}_4)_3$
Pyrope	$\text{Mg}_3\text{Al}_2(\text{SiO}_4)_3$
Almandite	$\text{Fe}_3\text{Al}_2(\text{SiO}_4)_3$
Spessartite	$\text{Mn}_3\text{Al}_2(\text{SiO}_4)_3$
Andradite	$\text{Ca}_3\text{Fe}_2(\text{SiO}_4)_3$
Uvarovite	$\text{Ca}_3\text{Cr}_2(\text{SiO}_4)_3$

It is rare to find a garnet that corresponds exactly to any one of these as can be seen from the following analyses:

Analyses of Garnets

	CaO	MgO	FeO	MnO	$\text{Al}_2\text{O}_3$	$\text{Fe}_2\text{O}_3$	$\text{Cr}_2\text{O}_3$	$\text{SiO}_2$
Grossularite .....	33.9	1.7	.....	.....	20.2	4.9	.....	39.5
Pyrope .....	5.0	17.9	8.1	0.5	22.4	5.5	.....	40.9
Almandite .....	1.4	3.6	33.8	1.1	22.7	.....	.....	37.6
Almandite .....	2.4	3.7	29.5	4.8	19.2	4.9	.....	35.9
Spessartite .....	0.5	.....	5.7	37.2	20.9	.....	.....	35.7
Andradite .....	31.5	tr.	0.3	.....	2.2	30.4	.....	35.3
Uvarovite .....	31.6	1.5	.....	.....	5.7	2.0	21.8	36.9

**Blowpipe Tests.** All are fusible (3 to 4) except uvarovite, which is infusible.

Insoluble before fusion, but after fusion (alone, not with  $\text{Na}_2\text{CO}_3$ ) it gelatinizes with HCl (except uvarovite).

**Uses.** Garnet is used as an abrasive, especially for finishing wood and leather. Some varieties are used for gems.

**Occurrence.** 1. In crystalline limestones especially at contacts, associated with wollastonite, diopside, vesuvianite, etc. (grossularite and andradite).

2. In schists and gneisses (almandite).

3. In eclogites with pyroxenes or amphiboles.
4. In granites and granite-pegmatites (almandite and spessartite).
5. In peridotites and derived serpentines (pyrope).
6. In nepheline- and leucite-bearing lavas, such as phonolites, etc. (*melanite* variety of andradite).
7. In seams of chromite as an alteration product (uvarovite).
8. In sands.

### OLIVINE, $(\text{Mg,Fe})_2\text{SiO}_4$

**Form.** For olivine the characteristic occurrences are granular masses or disseminated crystals and grains. Crystals are orthorhombic and are usually tabular in habit.

Fig. 557 represents a crystal with all the seven type forms of the rhombic bipyramidal class.  $a\{100\}$ ,  $b\{010\}$ ,  $c\{001\}$ ,  $m\{110\}$ ,  $d\{101\}$ ,  $k\{021\}$ ,  $p\{111\}$ .

$H. = 6\frac{1}{2}$  to 7.

$Sp. gr. \pm 3.3.$

**Color,** yellowish green to bottle green.

**Optical Properties.**  $n_r(1.70) - n_a(1.66) = 0.04$ . Fragments are irregular and colorless with bright interference colors.

**Chemical Composition.** Magnesium-iron orthosilicate  $(\text{Mg,Fe})_2\text{SiO}_4$ , varying from  $\text{Mg}_2\text{SiO}_4$  (*forsterite*) to  $\text{Fe}_2\text{SiO}_4$  (*fayalite*). The following analyses show the range in composition:

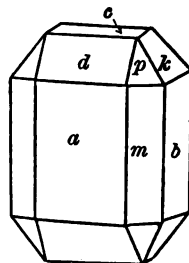


FIG. 557.

	MgO	FeO	CaO	SiO <sub>2</sub>	Misc.
Forsterite.....	54.4	1.5	0.8	42.8	ign. = 0.8
Olivine.....	50.3	8.5	.....	41.2	
Olivine.....	44.1	17.5	.....	39.2	
Olivine.....	30.6	28.1	1.4	38.9	MnO = 1.2
Fayalite.....	.....	65.5	.....	32.4	MnO = 2.1

**Blowpipe Tests.** Infusible.

Gelatinizes with HCl.

**Uses.** Clear transparent olivine is used as a gem under the name peridot.

**Occurrence.** 1. In peridotites with enstatite or diallage. The olivine is usually partially altered to serpentine. An igneous rock composed practically of olivine alone is called dunite.

2. In basalts, diabases, and gabbros. If the olivine is prominent, these rocks are called olivine-basalts, etc.

3. In tuffs and volcanic bombs.

4. In meteorites. Pallasite is a meteorite rock with olivine filling the cavities in a spongy mass of iron.

### WILLEMITE, $\text{Zn}_2\text{SiO}_4$

**Form.** This mineral is usually crystalline massive or granular massive. Crystals are hexagonal and prismatic in habit with the hexagonal prism  $\{11\bar{2}0\}$ , and the rhombohedron  $\{10\bar{1}1\}$ .

**H.** =  $5\frac{1}{2}$ .

**Sp. gr.**  $\pm 4.1$ .

**Color,** pale red, yellow to green.

**Optical Properties.**  $n_g(1.71) - n_a(1.69) = 0.02$ . Fragments are irregular with bright interference colors.

**Chemical Composition.** Zinc orthosilicate,  $\text{Zn}_2\text{SiO}_4$ ; (Zn = 58.0 per cent.). Manganese often replaces part of the zinc.

**Blowpipe Tests.** Fusible ( $5\frac{1}{2}$ ) with difficulty. With cobalt nitrate solution on charcoal the assay turns blue and the sublimate on the coal green. Willemite is distinguished from calamine by the absence of water in the closed tube.

It gives a fine jelly when dissolved in HCl.

**Uses.** Willemite is a source of zinc white and also of spelter.

**Occurrence.** 1. In crystalline limestone intimately mixed with franklinite and zincite. It perhaps has been formed by the metamorphism of calamine present in the original sedimentary limestone. Franklin Furnace, New Jersey.

**WERNERITE**,  $m\text{Ca}_4\text{Al}_6\text{Si}_6\text{O}_{25} + n\text{Na}_4\text{Al}_3\text{Si}_3\text{O}_{24}\text{Cl}$ 

**Form.** Wernerite occurs in rough crystals, in cleavable, columnar, and massive forms. Crystals are tetragonal (tetragonal bipyramidal class), prismatic in habit and often resemble diopside or augite crystals. The usual forms are  $a\{100\}$ ,  $m\{110\}$ ,  $r\{111\}$ , and  $\{101\}$ . Interfacial angles:  $rr(111:\bar{1}11) = 43^\circ 45'$ ,  $mr(110:111) = 58^\circ 12'$ ,  $am(100:110) = 45^\circ$ .

Fig. 558 represents a typical wernerite crystal.

**Cleavage**, imperfect parallel to  $\{100\}$  and  $\{110\}$ , so in four directions in one zone at angles of  $45^\circ$ .

**H.** =  $5\frac{1}{2}$ .

**Sp. gr.**  $\pm 2.7$ .

**Color**, white, gray, greenish, or reddish.

**Optical Properties.**  $n_r(1.57) - n_a(1.55) = 0.02$ . Fragments are prismatic with parallel extinction, bright interference colors, and negative elongation.

**Chemical Composition.** An isomorphous mixture of calcium aluminum silicate with sodium aluminum chlorid-silicate in varying proportions.

**Blowpipe Tests.** Easily fusible (3) to a white glass with intumescence coloring the flame yellow.

Partially decomposed by HCl.

**Occurrence.** 1. In crystalline limestones at the contact with igneous rocks and associated with diopside, garnet, and other silicates.

2. In gabbros along the border of apatite veins. Formed from plagioclase by the pneumatolytic process known as scapolitization.

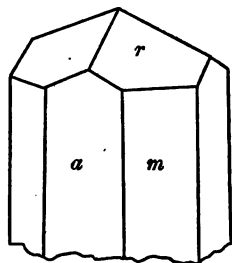


FIG. 558.

**VESUVIANITE**,  $\text{Ca}_4\text{Al}_3(\text{OH},\text{F})(\text{SiO}_4)_5$ 

**Form.** For vesuvianite the characteristic form is striated columnar masses, but crystals belonging to the tetragonal system are also common. The usual forms are  $m\{110\}$ ,  $c\{001\}$ ,  $p\{111\}$

The interfacial angles are  $cp(001:111)=37^\circ 13\frac{1}{2}'$ ;  $pp(111:\bar{1}\bar{1}1)=50^\circ 39'$ ;  $am(100:110)=45^\circ 0'$ . The habit is prismatic or low pyramidal and the cross-section is usually square. Fig. 559 is a drawing of a typical vesuvianite crystal.

H. =  $6\frac{1}{2}$ .

Sp. gr.  $\pm 3.4$ .

Color, green, yellow-brown, or greenish-brown.

**Optical Properties.**  $n_r(1.723) - n_a(1.722) = 0.001$ . Fragments are irregular with very low first order anomalous interference colors.

**Chemical Composition.** Basic calcium aluminum orthosilicate,  $\text{Ca}_6\text{Al}_2(\text{OH},\text{F})(\text{SiO}_4)_8$ . Iron replaces part of the aluminum and magnesium, part of the calcium.

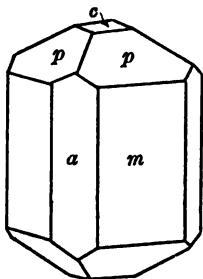


FIG. 559.

**Blowpipe Tests.** Fuses at 3 with intumescence to a colored glass. In the closed tube at a high temperature it gives a little water (about 2 per cent.).

Slightly decomposed by HCl. After fusion (alone) it gelatinizes with HCl.

**Occurrence.** 1. In crystalline limestones at the contact with igneous rocks and associated with garnet, diopside, wollastonite, etc.

## ZIRCON, $\text{ZrSiO}_4$

**Form.** Zircon is practically always found in crystals which are either embedded or loose occurring in sands.

Zircon is one of the best examples of the ditetragonal bipyramidal class of the tetragonal system.  $c=0.640$ . Usual forms:  $m\{110\}$ ,  $a\{100\}$ ,  $p\{111\}$ ,  $u\{331\}$ ,  $x\{131\}$ . Interfacial angles:  $pp(111:\bar{1}\bar{1}1)=56^\circ 40'$ ;  $mp(110:111)=47^\circ 50'$ ;  $ap(100:111)=61^\circ 40'$ ;  $mu(110:331)=20^\circ 12'$ . The habit is low pyramidal or prismatic (Figs. 560 to 563).

H. =  $7\frac{1}{2}$ .

Sp. gr.  $\pm 4.6$ .

**Color**, usually brown but also red, yellow, and colorless. Luster, adamantine.

**Optical Properties.**  $n_r(1.98) - n_a(1.93) = 0.05$ . Fragments are irregular with high order interference colors.

**Chemical Composition.** Zirconium orthosilicate,  $\text{ZrSiO}_4$ .

**Blowpipe Tests.** Infusible, but loses color.

Insoluble in acids.

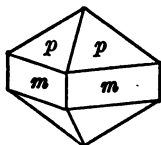


FIG. 560.

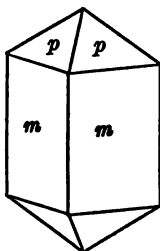


FIG. 561.

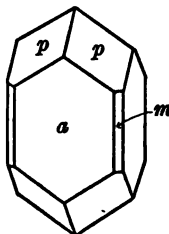


FIG. 562.

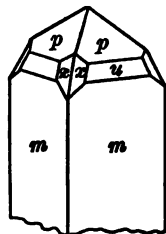


FIG. 563

**Uses.** Certain kinds of zircon called hyacinth are used as gems. Zircon is the source of zirconia ( $\text{ZrO}_2$ ) used as a glower in the Nernst lamp.

**Occurrence.** 1. In igneous rocks especially the acid rocks rich in soda such as syenites and soda-granites.

2. In sands and gravels. Ceylon.

### TOPAZ, $\text{Al}_2\text{F}_2\text{SiO}_4$

**Form.** Topaz occurs in well-defined crystals and in cleavable masses. Topaz crystallizes in the bipyramidal class of the orthorhombic system.  $a:b:c = 0.528:1:0.477$ . Usual forms:  $m\{110\}$ ,  $l\{120\}$ ,  $c\{001\}$ ,  $f\{021\}$ ,  $y\{041\}$ ,  $u\{111\}$ ,  $o\{221\}$ ,  $i\{223\}$ . Interfacial angles:  $mm(110:1\bar{1}0) = 55^\circ 43'$ ;  $ll(120:\bar{1}20) = 86^\circ 49'$ ;  $ml(110:120) = 79^\circ 44'$ ;  $ff(021:0\bar{2}1) = 87^\circ 18'$ ;  $yy(041:0\bar{4}1) = 124^\circ 41'$ ;  $ci(001:223) = 34^\circ 14'$ ;  $cu(001:111) = 45^\circ 35'$ ;  $co(001:221) = 63^\circ 54'$ . The habit is usually prismatic, with  $m\{110\}$  and  $l\{120\}$  about equally developed. Figs. 564–567 represent typical crystals.



**Cleavage**, perfect in one direction parallel to  $\{001\}$ .

**H.** = 8.

**Sp. gr.**  $\pm 3.5$ .

**Color**, colorless, white, yellowish, bluish, reddish.

**Optical Properties.**  $n_r(1.622) - n_a(1.613) = 0.009$ . Fragments are plates with irregular outline and low first order positive interference colors. Cleavage flakes give a positive biaxial interference figure. The optical orientation of topaz is  $\alpha = a$ ,  $\beta = b$ ,  $\gamma = c$ ; hence (010) is the axial plane.

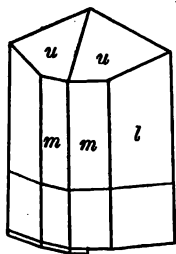


FIG. 564.

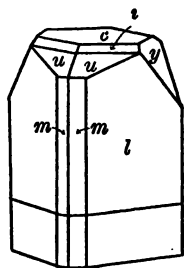


FIG. 565.

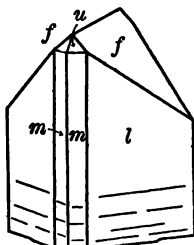


FIG. 566.

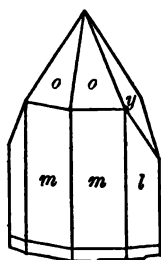


FIG. 567.

**Chemical Composition.** Aluminum fluorid-silicate,  $\text{Al}_2\text{F}_2\text{SiO}_4$ , or  $2\text{AlF}_3 \cdot \text{Al}_4(\text{SiO}_4)_3$ . Hydroxyl replaces part of the fluorin.

**Blowpipe Tests.** Infusible. With cobalt nitrate solution it gives a deep blue color. On intense ignition in a closed tube some varieties give a little water. Heated with  $\text{NaPO}_3$  in the closed tube etches the tube.

Partially decomposed by  $\text{H}_2\text{SO}_4$ .

**Uses.** Topaz is sometimes used as a gem.

**Occurrence.** 1. In granite-pegmatites and surrounding rocks associated with tourmaline, lepidolite, albite, fluorite, apatite, beryl, etc. El Paso County, Colorado.

### Sillimanite, $\text{Al}_2\text{OSiO}_4$

**Form.** In prismatic and acicular crystals and in fibrous masses. Sillimanite crystallizes in the orthorhombic system, but

distinct crystals are rare. The prism faces with  $(110:1\bar{1}0=88^\circ)$  are usually the only forms present.

**H.** =  $6\frac{1}{2}$ .

**Sp. gr.**  $\pm 3.2$ .

**Color**, brown, gray, or white.

**Optical Properties.**  $n_r(1.68) - n_a(1.66) = 0.02$ . Fragments are prismatic or acicular with parallel extinction and positive elongation. The interference colors are bright.

**Chemical Composition.** Aluminum oxid-silicate,  $\text{Al}_2\text{OSiO}_4$ , or  $\text{Al}_2\text{O}_3 \cdot \text{Al}_4(\text{SiO}_4)_3$ .

**Blowpipe Tests.** Infusible. It turns blue with cobalt nitrate solution.

Insoluble in acids.

**Occurrence.** 1. In gneisses and schists, apparently always the result of metamorphism.

On heating to  $1350^\circ \text{C.}$ , andalusite and cyanite change into sillimanite.

### ANDALUSITE, $\text{Al}_2\text{OSiO}_4$

**Form.** Andalusite occurs in rough, attached or embedded crystals, in columnar masses, and in rolled pebbles. The crystals are orthorhombic and prismatic in habit, the only common forms being  $\{110\}$  and  $\{001\}$  with a prism angle of  $89^\circ 12'$  ( $110:1\bar{1}0$ ). (Fig. 568.)

**H.** =  $7\frac{1}{2}$ .

**Sp. gr.**  $\pm 3.1$ .

**Color**, usually gray, often with symmetrically arranged white or black areas. (See Fig. 568).

**Optical Properties.**  $n_r(1.64) - n_a(1.63) = 0.01$ . Fragments are irregular or prismatic with parallel extinction and colorless or pleochroic from reddish to greenish. The interference colors are low first order.

**Chemical Composition.** Aluminum oxid-silicate,  $\text{Al}_2\text{OSiO}_4$ , or  $\text{Al}_2\text{O}_3 \cdot \text{Al}_4(\text{SiO}_4)_3$ .

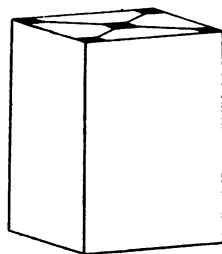


FIG. 568.

**Blowpipe Tests.** Infusible. It turns blue when heated with cobalt nitrate solution.

Insoluble in acids.

**Occurrence.** 1. In schists and slates as a product of contact metamorphism. Lancaster, Massachusetts.

### · **CYANITE, $\text{Al}_2\text{OSiO}_4$**

**Form.** For cyanite the characteristic form is bladed crystals or crystal aggregates. Crystals are triclinic, tabular parallel to  $\{100\}$ , and elongated in the direction of the  $c$ -axis.

**Cleavage,** perfect in one direction parallel to  $\{100\}$ . There are imperfect cleavages in other directions.

**H.** =  $4\frac{1}{2}$  (parallel to the length) and 7 (perpendicular to the length).

**Sp. gr.**  $\pm 3.6$ .

**Color,** blue, bluish-gray, green, or white, often colored in spots and streaks.

**Optical Properties.**  $n_r(1.728) - n_a(1.712) = 0.016$ . Fragments are prismatic or acicular with oblique extinction of  $30^\circ$  and bright interference colors. Cleavage flakes give a biaxial interference figure with the axial plane oblique to the edge.

**Chemical Composition.** Aluminum oxid-silicate,  $\text{Al}_2\text{OSiO}_4$  or  $\text{Al}_2\text{O}_3 \cdot \text{Al}_4(\text{SiO}_4)_3$ . Sillimanite, andalusite, and cyanite all have the same composition, but differ in physical properties.

**Blowpipe Tests.** Infusible. It turns blue with cobalt nitrate solution.

Insoluble in acids.

**Occurrence.** 1. In schists and gneisses as the product of metamorphism.

### **DATOLITE, $\text{CaB}(\text{OH})\text{SiO}_4$**

**Form.** Datolite occurs in crystals, crystalline druses, and crystalline masses. Crystals are monoclinic and are usually complex and difficult to decipher. As the angle  $\beta$  (between the  $a$ - and  $c$ -axes) is  $89^\circ 51'$ , the crystals often appear to be orthorhombic. Fig. 569 is an orthographic projection of a datolite crystal.

**H.** =  $5\frac{1}{2}$ .

**Sp. gr.**  $\pm 2.9$ .

**Color**, colorless, white, pale green.

**Optical Properties.**  $n_r(1.670) - n_a(1.626) = 0.044$ . Fragments are irregular with bright interference colors.

**Chemical Composition.** Basic calcium boron orthosilicate,  $\text{CaB}(\text{OH})\text{SiO}_4$ ; ( $\text{H}_2\text{O} = 5.6$  per cent.).

**Blowpipe Tests.** Easily fusible (2) to a glass, with intumescence coloring the flame green. In the closed tube it gives water.

Gelatinizes with  $\text{HCl}$ .

**Occurrence.** 1. A secondary mineral in cavities of diabases and basalts associated with the zeolites, apophyllite, prehnite, and pectolite.

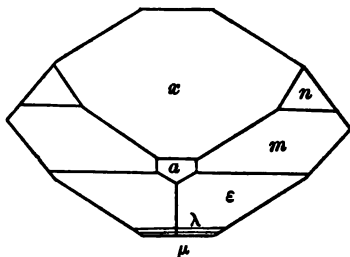


FIG. 569.

### Zoisite, $\text{HCa}_2\text{Al}_3(\text{SiO}_4)_3$

**Form.** Zoisite is usually found in columnar masses. Orthorhombic crystals are rare.

**Cleavage**, perfect in one direction (010).

**H.** = 6 to  $6\frac{1}{2}$ .

**Sp. gr.**  $\pm 3.3$ .

**Color**, usually gray.

**Optical Properties.**  $n_r(1.702) - n_a(1.697) = 0.005$ . Fragments are prismatic with parallel extinction, negative elongation, and low first order interference colors which are often Berlin blue.

**Chemical Composition.** Acid calcium aluminum orthosilicate,  $\text{HCa}_2\text{Al}_3(\text{SiO}_4)_3$ ; ( $\text{H}_2\text{O} = 4.4$  per cent.).

**Blowpipe Tests.** Fusible at 3 to a white glass. In the closed tube it yields water.

Insoluble in acids, but after fusion gelatinizes with  $\text{HCl}$ .

**Occurrence.** 1. In metamorphic rocks, especially hornblende and glaucophane schists.

### EPIDOTE, $\text{Ca}_2(\text{Al,Fe})_3(\text{OH})(\text{SiO}_4)_3$

**Form.** In crystals, in columnar aggregates, and in granular masses. The crystals are monoclinic, prismatic in habit, and are elongated in the direction of the  $b$ -axis instead of the  $c$ -axis, as in most monoclinic minerals. Usual forms:  $a\{100\}$ ,  $b\{010\}$ ,  $c\{001\}$ ,  $u\{120\}$ ,  $r\{\bar{1}01\}$ ,  $n\{\bar{1}11\}$ . Interfacial angles:  $ac(100:001)=64^\circ 37'$ ;  $cr(001:\bar{1}01)=63^\circ 42'$ ;  $nn(\bar{1}11:\bar{1}\bar{1}\bar{1})=70^\circ 29'$ .  $au(100:210)=35^\circ 29\frac{1}{2}'$ . Fig. 570 is a cross-section of a typical crystal, while Fig. 571 is the cross-section of a twin crystal with  $a\{100\}$  as twin plane.

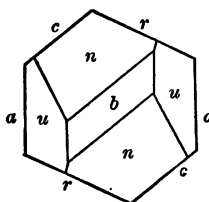


FIG. 570.

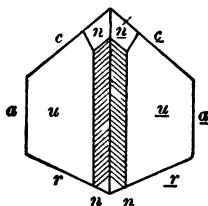


FIG. 571.

**Cleavage**,  $\{001\}$  perfect;  $\{100\}$  imperfect.

**H.**  $=6\frac{1}{2}$ .

**Sp. gr.**  $\pm 3.4$ .

**Color**, usually pistache-green, but varies from gray through yellow to deep brownish-green and almost black, according to the amount of iron present.

**Optical Properties.**  $n_\gamma(1.767) - n_\alpha(1.730) = 0.037$ . Fragments are irregular or prismatic with parallel extinction. The interference colors are bright. The deep colored varieties are pleochroic from colorless to pale green. Cleavage flakes give an interference figure consisting of an axial bar with concentric rings.

**Chemical Composition.** Basic calcium aluminum-iron orthosilicate,  $\text{Ca}_2(\text{Al,Fe})_3(\text{OH})(\text{SiO}_4)_3$ , an isomorphous mixture of  $\text{Ca}_2\text{Al}_3(\text{OH})(\text{SiO}_4)_3$ , a mineral called clinozoisite, and  $\text{Ca}_2\text{Fe}_3(\text{OH})(\text{SiO}_4)_3$ , not yet discovered. The following analyses illustrate the isomorphism.

	CaO	FeO	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	H <sub>2</sub> O	
Clinozoisite ...	24.5	0.3	32.6	1.7	39.1	....	MnO=0.2
Epidote .....	23.8	0.5	29.5	5.7	38.0	2.0	
Epidote .....	23.9	....	26.5	8.2	39.2	2.2	
Epidote .....	23.3	0.9	22.6	14.0	37.8	2.1	

**Blowpipe Tests.** Fusible at 3 to a colored glass with intumescence. In the closed tube at a high temperature it gives a little water (about 2 per cent.).

Partially decomposed by HCl. After fusion (alone) it gelatinizes with HCl.

**Occurrence.** 1. At the contact between igneous rocks, especially granites, and limestones, often associated with copper minerals.

2. As a weathering product along seams of igneous rocks, especially granites.

3. In schists, especially as the product of intense folding, associated with hornblende. New York City.

#### Allanite, $(\text{Ca}, \text{Fe})(\text{Al}, \text{Ce}, \text{Fe})_3(\text{OH})(\text{SiO}_4)_3$

**Form.** Allanite occurs in rough crystals, in masses, and in embedded grains. Crystals are monoclinic and usually tabular parallel to {100}.

**H.** =  $5\frac{1}{2}$  to 6.

**Sp. gr.** from 3 to 4.

**Color,** black. Luster, submetallic.

**Optical Properties.**  $n_p = 1.68$ . Fragments are irregular, brownish, and slightly pleochroic. Isotropic or with low first order interference colors.

**Chemical Composition.** A basic orthosilicate similar to epidote, but with calcium partly replaced by ferrous iron and aluminum and ferric iron partly replaced by cerium and other rare earth metals.

**Blowpipe Tests.** Easily fusible at  $2\frac{1}{2}$  to a dark magnetic globule. In the closed tube it gives water, but usually only at a high temperature.

Gelatinizes with HCl.

**Occurrence.** 1. As an accessory constituent of igneous rocks, sometimes intergrown with epidote.

**Axinite,  $\text{HCa}_2(\text{Fe,Mn})\text{Al}_2\text{B}(\text{SiO}_4)_4$**

**Form.** Axinite occurs in crystals and crystalline aggregates. The crystals furnish about the best known examples of triclinic crystals. The habit is usually tabular and the cross-sections shaped-wedge. Fig. 109, page 38, represents a typical crystal.

H. =  $6\frac{1}{2}$  to 7.

Sp. gr.  $\pm 3.3$ .

Color, violet, brown, smoky gray.

**Optical Properties.**  $n_r(1.68) - n_a(1.67) = 0.01$ . Fragments are irregular with interference colors. Thick fragments are pleochroic.

**Chemical Composition.** An acid calcium iron-manganese aluminum boron silicate,  $\text{HCa}_2(\text{Fe,Mn})\text{Al}_2\text{B}(\text{SiO}_4)_4$ .

**Blowpipe Tests.** Easily fusible ( $2\frac{1}{2}$ ) with intumescence to a dark glass. In the closed tube at a high temperature gives a little water. Fused with  $\text{KHSO}_4$  and  $\text{CaF}_2$  it gives a green flame.

Insoluble in HCl.

**Occurrence.** 1. At the contact of granites with basic lime-rich rocks such as schists and impure limestones.

**PREHNITE,  $\text{H}_2\text{Ca}_2\text{Al}_2(\text{SiO}_4)_3$**

**Form.** Prehnite is found in crystalline druses and seams. Distinct crystals (orthorhombic) are very rare. The imperfect crystals are usually grouped in mammillary and globular forms, showing a series of ridges.

H. = 6 to  $6\frac{1}{2}$ .

Sp. gr.  $\pm 2.9$ .

Color, usually pale green or white.

**Optical Properties.**  $n_r(1.65) - n_a(1.62) = 0.03$ . Fragments are irregular with bright interference colors.

**Chemical Composition.** Acid calcium aluminum orthosilicate,  $\text{H}_2\text{Ca}_2\text{Al}_2(\text{SiO}_4)_3$ ; ( $\text{H}_2\text{O} = 4.4$  per cent.).

**Blowpipe Tests.** Easily fusible (2) with intumescence to a white glass. In the closed tube it gives water.

Decomposed by  $\text{HCl}$  and after fusion (alone) gelatinizes with  $\text{HCl}$ .

**Occurrence.** 1. A secondary mineral in cavities of diabases and basalts associated with datolite, pectolite, apophyllite, and the zeolites.

### Chondrodite, $\text{Mg}_6(\text{F,OH})_2(\text{SiO}_4)_2$

**Form.** Chondrodite occurs in disseminated crystals and grains and is also sometimes massive. Crystals are monoclinic, equidimensional, but rather complex.

**H.** = 6 to  $6\frac{1}{2}$ .

**Sp. gr.**  $\pm 3.1$ .

**Color,** red, orange, yellow, brown.

**Optical Properties.**  $n_\gamma(1.64) - n_\alpha(1.61) = 0.03$ . Fragments are irregular and colorless, or yellow with slight pleochroism. The interference colors are bright.

**Chemical Composition.** Basic magnesium orthosilicate,  $\text{Mg}_6(\text{F,OH})_2(\text{SiO}_4)_2$  or  $\text{Mg}(\text{F,OH})_2 \cdot 2\text{Mg}_2\text{SiO}_4$ . Iron replaces part of the magnesium and hydroxyl part of the fluorin.

**Blowpipe Tests.** Infusible. In the closed tube it gives a little water (about 1.3 per cent.) at a high temperature. In the closed tube with  $\text{NaPO}_3$  etches the inside of the tube.

Gelatinizes with  $\text{HCl}$ .

**Occurrence.** 1. In crystalline limestones with phlogopite, spinel, etc. Sparta, New Jersey.

## MICA GROUP

The micas are acid orthosilicates of aluminum with magnesium, ferrous iron, and the alkalis. On heating at a high temperature they give off from 2 to 5 per cent. of water.

The micas are monoclinic, but pseudohexagonal in habit. Dis-



tinct terminated crystals are very rare. The very perfect cleavage parallel to {001} is the most striking feature of the micas. The micas are optically biaxial with varying axial angle. In the absence of crystal faces cleavage plates of the micas may be oriented by means of the percussion figure in connection with the interference figure. A sharp, quick blow with a dull conical point develops a six-rayed star. If the interference figure lies along one of the rays then that ray is the direction of the *b*-axis.

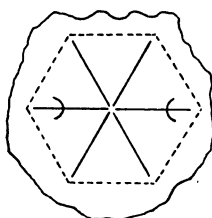


FIG. 572.  
Mica of the first class.

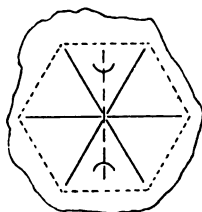


FIG. 573.  
Mica of the second class.

These are *micas of the first class* and are represented by Fig. 572. If the interference figure lies between two rays of the percussion figure, then the third ray is the direction of the *b*-axis. These are *micas of the second class* and are represented by Fig. 573. Muscovite and lepidolite are micas of the first class, while biotite and phlogopite are micas of the second class.

### MUSCOVITE, $\text{H}_2\text{KAl}_2(\text{SiO}_4)_2$

**Form.** Muscovite usually occurs in cleavages and scaly masses and but rarely in well-defined crystals. The crystals are tabular in habit, and pseudohexagonal or pseudorhombic, but are really monoclinic. Fig. 574 represents a muscovite crystal, the side elevation on the right proving it to be monoclinic.

**Cleavage**, very perfect in one direction parallel to {001}.

**H.** = 2 to  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 2.8$ .

**Color,** colorless, pale green, or pale brown. Thin sheets are always transparent.

**Optical Properties.**  $n_r(1.597) - n_a(1.560) = 0.037$ . Cleavage flakes give low first order interference colors and in convergent light, a fine negative biaxial interference figure with large axial angle ( $2E=60^\circ$  to  $75^\circ$ ).

**Chemical Composition.** An acid potassium aluminum orthosilicate,  $H_2KAl_3(SiO_4)_3$ ; ( $H_2O=4.5$  per cent.).

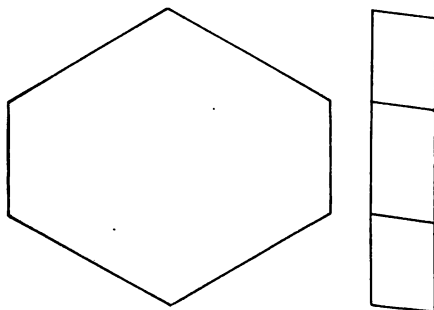


FIG. 574.

**Blowpipe Tests.** Fusible on thin edges (5) and whitens. In the closed tube it gives a little water.

Insoluble in acids and not decomposed by  $H_2SO_4$ .

**Uses.** Muscovite is used principally as an insulator for electrical apparatus, but has numerous other uses.

**Occurrence.** 1. In granite-pegmatites and granite-aplites.

2. In schists and gneisses, often the main constituent of the mica-schists.

3. In granites. Granite is about the only igneous rock in which muscovite occurs as an original constituent.

4. In sandstones and sands as a detrital mineral.

5. As a secondary mineral derived from other silicates, especially the feldspars. This variety is called *sericite* and the alteration process is known as sericitization.

**LEPIDOLITE,  $\text{LiKAl}_2(\text{OH,F})(\text{SiO}_3)_3$** 

**Form.** Lepidolite usually occurs in scaly masses, rarely in crystals. Crystals are pseudohexagonal like those of muscovite, but are much smaller.

**Cleavage** in one direction.

**H.** =  $2\frac{1}{2}$  to  $3\frac{1}{2}$ .

**Sp. gr.**  $\pm 2.8$ .

**Color**, pale to deep lilac.

**Optical Properties.**  $n_\gamma(1.60) - n_\beta(1.56) = 0.04$ . Cleavage flakes give low first order interference colors and in convergent light a negative, biaxial interference figure with large axial angle ( $2E = 60^\circ$  to  $80^\circ$ ).

**Chemical Composition.** Lithium potassium aluminum fluorid metasilicate,  $\text{LiKAl}_2(\text{OH,F})(\text{SiO}_3)_3$ .

**Blowpipe Tests.** Easily fusible at 2 with intumescence to a white glass, coloring the flame purple. In the closed tube on intense ignition it gives water which has an acid reaction due to the HF formed.

Partially decomposed by HCl. After fusion gelatinizes with HCl.

**Uses.** Lepidolite is a source of lithium salts.

**Occurrence.** 1. In granite-pegmatites and surrounding granites associated with tourmaline, albite, muscovite, spodumene, amblygonite, etc. Pala, San Diego County, California.

**BIOTITE,  $(\text{H,K})(\text{Mg,Fe})\text{Al}_2(\text{SiO}_3)_3$** 

**Form.** Biotite occurs in embedded crystals and disseminated scales and in lamellar masses. Crystals are pseudohexagonal like those of muscovite.

**Cleavage**, very perfect in one direction.

**H.** =  $2\frac{1}{2}$  to 3.

**Sp. gr.**  $\pm 2.9$ .

**Color**, black or dark brown. Thin sheets are translucent.

**Optical Properties.**  $n_\gamma(1.60) - n_\alpha(1.57) = 0.03$ . Cleavage flakes are almost dark between crossed nicols and in convergent light

give a negative biaxial interference figure with a small axial angle ( $2E=0-20^\circ$ ). It is sometimes practically uniaxial.

**Chemical Composition.** Acid-potassium magnesium-iron aluminum orthosilicate  $(H,K)_2(Mg,Fe)_2Al_2(SiO_4)_3$ .

**Blowpipe Tests.** Fusible on edges (5) and turns white. In the closed tube gives a little water (2 to 4 per cent.) on intense ignition.

Decomposed by concentrated  $H_2SO_4$ .

**Occurrence.** 1. In many kinds of igneous rocks, but especially prominent in granites, and in certain dike rocks known as lamprophyrs.

2. In schists and gneisses, sometimes as the dominant mineral. Biotite is often associated with muscovite.

### PHLOGOPITE, $H_2KMg_3Al(SiO_4)_3$

**Form.** Like the other micas phlogopite occurs in crystals, in disseminated scales, and in lamellar masses. The crystals are pseudohexagonal, but are often prismatic in habit as well as tabular.

**Cleavage,** very perfect in one direction.

$H.=2\frac{1}{2}$  to 3.

$Sp. gr. \pm 2.8$ .

**Color,** bronze, brown, yellow.

**Optical Properties.**  $n_\gamma(1.60) - n_\alpha(1.56) = 0.04$ . Cleavage flakes give very low first order interference colors and in convergent light, a negative biaxial interference figure with a small axial angle ( $2E=5^\circ$  to  $20^\circ$ ).

**Chemical Composition.** Acid potassium magnesium aluminum orthosilicate,  $H_2KMg_3Al(SiO_4)_3$ . Also contains iron and fluorin.

**Blowpipe Tests.** Fusible (5) on thin edges and whitens. In the closed tube it gives a little water on intense ignition.

Easily decomposed by concentrated  $H_2SO_4$ .

**Uses.** Phlogopite is used principally as an insulator in electrical apparatus.

**Occurrence.** 1. In crystalline limestones associated with spinel, graphite, chondrodite, etc.

## D. MISCELLANEOUS ANHYDROUS SILICATES

Iolite,	$(\text{Mg,Fe})_4\text{Al}_3(\text{OH})_2(\text{Si}_2\text{O}_7)_5$
TOURMALINE,	$\text{R}_3^1\text{Al}_3\text{B}_2(\text{OH})_2\text{Si}_4\text{O}_{19}$
STAUROLITE,	$\text{FeAl}_3(\text{OH})(\text{SiO}_3)_2$
Margarite,	$\text{H}_2\text{CaAl}_4(\text{SiO}_3)_2$
CHLORITE,	$\text{H}_3(\text{Mg,Fe})_3\text{Al}_2(\text{SiO}_3)_3$
SERPENTINE,	$\text{H}_4\text{Mg}_3\text{Si}_2\text{O}_9$
Sepiolite,	$\text{H}_4\text{Mg}_2\text{Si}_4\text{O}_{10}$
Kaolinite,	$\text{H}_4\text{Al}_2\text{Si}_2\text{O}_9$
Lawsonite,	$\text{H}_4\text{CaAl}_2(\text{SiO}_3)_2$
TITANITE,	$\text{CaTiSiO}_5$



**Form.** Iolite occurs in orthorhombic (pseudohexagonal) crystals of short prismatic habit. It is also massive.

**Cleavage,** indistinct.

**H.** = 7 to  $7\frac{1}{2}$ .

**Sp. gr.**  $\pm 2.6$ .

**Color,** blue to colorless. Luster, vitreous like quartz.

**Optical Properties.**  $n_r(1.54) - n_a(1.53) = 0.01$ . Fragments are irregular with low first order interference colors. In thick fragments iolite is pleochroic from dark blue to light blue, blue to colorless, or blue to yellowish.

**Chemical Composition.** A basic magnesium-iron aluminum diorthosilicate  $(\text{Mg,Fe})_4\text{Al}_3(\text{OH})_2(\text{Si}_2\text{O}_7)_5$ .

**Blowpipe Tests.** Fuses with difficulty (5) and becomes opaque. Partially decomposed by acids.

**Uses.** Iolite is sometimes used as a gem.

**Occurrence.** 1. In gneisses. Guilford, Connecticut.

2. As a contact mineral in slates. Japan.



**Form.** Tourmaline usually occurs in distinct attached or embedded crystals, and in columnar subradiating aggregates. Tourmaline is the type example of the ditrigonal pyramidal class

of the hexagonal system.  $c=0.447$ . Usual forms:  $a\{11\bar{2}0\}$ ,  $m\{10\bar{1}0\}$ ,  $m_1\{01\bar{1}0\}$ ,  $r\{10\bar{1}1\}$ ,  $\bar{c}\{01\bar{1}2\}$ ,  $o\{02\bar{2}1\}$ ,  $c\{0001\}$ ,  $t\{21\bar{3}1\}$ ,  $u\{32\bar{5}1\}$ ,  $x\{12\bar{3}2\}$ ,  $r_1\{01\bar{1}1\}$ ,  $e_1\{10\bar{1}2\}$ ,  $c_1\{000\bar{1}\}$ . Interfacial angles:  $rm(10\bar{1}1:10\bar{1}0)=62^\circ 40'$ ;  $em_1(01\bar{1}2:01\bar{1}0)=75^\circ 30\frac{1}{2}'$ ;  $om_1(02\bar{2}1:01\bar{1}0)=44^\circ 3'$ ;  $ee(01\bar{1}2:\bar{1}012)=25^\circ 2'$ ;  $rr(10\bar{1}1:\bar{1}101)=46^\circ 52'$ ;  $oo(02\bar{2}1:\bar{2}021)=77^\circ 0'$ ;  $xx(12\bar{3}2:\bar{1}3\bar{2}2)=21^\circ 18'$ ;  $xx(12\bar{3}2:3\bar{2}\bar{1}2)=43^\circ 22\frac{1}{2}'$ ;  $tt(21\bar{3}1:\bar{2}3\bar{1}1)=63^\circ 48'$ ;  $tt(21\bar{3}1:3\bar{1}\bar{2}1)=30^\circ 38\frac{1}{2}'$ .

The habit is short to long prismatic and the cross-section three-, six-, or nine-sided, very often being rounded triangular like a spherical triangle. The two ends of the crystals are usually differently terminated. Figs. 575 to 578 represent typical tourmaline crystals.

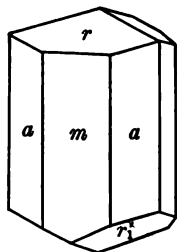


FIG. 575.

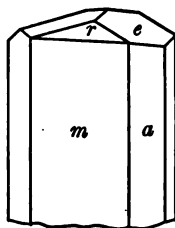


FIG. 576.

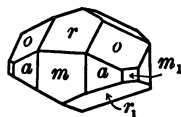


FIG. 577.

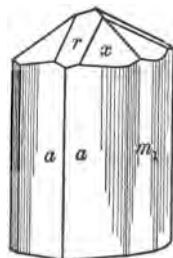


FIG. 578.

**Cleavage**, none. The absence of cleavage distinguishes tourmaline from hornblende.

**H.** = 7 to  $7\frac{1}{2}$ .

**Sp. gr.**  $\pm 3.1$ .

**Color**, black, brown, green, blue, red, pink, colorless. The exterior and interior and also the opposite ends of a crystal often differ in color. Transparent colored crystals show pleochroism with a dichroscope.

Tourmaline is pyroelectric, that is, a crystal which has been heated will, on cooling, develop positive electricity at one end and negative electricity at the other. This may be tested with a fine hair.

**Optical Properties.**  $n_r(1.65) - n_a(1.63) = 0.02$ . Fragments are irregular or prismatic with parallel extinction. The interference colors are bright. The black and deep colored varieties are pleochroic (often from blue to smoke-colored), while the light colored varieties are colorless, but in thick fragments or small crystals are also pleochroic.

**Chemical Composition.** A complex silicate of aluminum, boron, iron, magnesium, and the alkalis. No satisfactory formula has yet been established. Penfield gives  $R_3^1Al_3B_3(OH)_2Si_4O_{19}$ , in which  $R^1$  is iron, magnesium, and the alkalis. The following are typical analyses:

Analyses of Tourmaline

	Li <sub>2</sub> O	Na <sub>2</sub> O	H <sub>2</sub> O	FeO	MgO	Al <sub>2</sub> O <sub>3</sub>	B <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Misc.
1. Pink.....	1.9	2.1	3.4	0.2	.....	42.2	10.6	37.6	2.0
2. Pale green...	1.8	2.2	3.3	1.5	.....	41.3	10.6	36.7	3.8
3. Brown.....	tr	0.9	3.1	0.9	14.6	28.5	10.4	35.3	Ca-5.1
4. Black.....	tr	2.2	3.6	11.9	4.5	31.1	9.9	34.9	2.2
5. Black.....	tr	2.0	3.6	14.2	1.0	33.9	9.6	35.0	0.6

Three principal varieties based upon composition and color are recognized namely; (1) iron tourmaline, black (analyses 4 and 5), (2) magnesium tourmaline, brown (analysis 3), (3) alkali tourmaline, red, green, or blue (analyses 1 and 2).

**Blowpipe Tests.** The fusibility varies from easy fusibility at 3 (magnesium variety) to infusibility (alkali variety). In the closed tube at a very high temperature it gives water (from 2 to 4 per cent.). Tourmaline gives a green flame when fused with boracic acid flux.

Insoluble in acids. After fusion (alone) it gelatinizes with HCl.

**Uses.** Colored tourmaline is used as a gem.

**Occurrence.** 1. In granite-pegmatites often associated with albite, lepidolite, beryl, apatite, fluorite, etc. Pala, San Diego County, California.

2. In rocks surrounding pegmatites often associated with cassiterite, topaz, etc. In greisen, a quartz-muscovite rock formed from granite by pneumatolysis; in luxullianite, a variety of quartz-porphyry in which the quartz is partly replaced by tourmaline; and in tourmaline schists. Jefferson County, Colorado.

3. In crystalline limestones (the brown magnesium variety), associated with spinel, phlogopite, corundum, etc. Hamburg, New Jersey.

4. In veins with copper minerals.

5. In sands. Brazil.

### STAUROLITE, $\text{FeAl}_3(\text{OH})(\text{SiO}_3)_2$

**Form.** Staurolite crystallizes in the orthorhombic system and is rarely found massive. The habit is prismatic with the forms  $c\{001\}$ ,  $m\{110\}$ ,  $b\{010\}$ , and  $r\{101\}$  (Fig. 579). Interfacial angles:  $mm(110:1\bar{1}0) = 50^\circ 40'$ ;  $cr(001:101) = 55^\circ 16'$ . Cruciform penetration twins with  $\{032\}$  as twin-plane are common.

**H.** = 7 to  $7\frac{1}{2}$ .

**Sp. gr.**  $\pm 3.7$ .

**Color,** brown.

**Optical Properties.**  $n_r(1.74) - n_a(1.73) = 0.01$ . Fragments are irregular with upper first order interference colors and are pleochroic from light to deep yellow.

**Chemical Composition.** Basic iron aluminum silicate,  $\text{FeAl}_3(\text{OH})(\text{SiO}_3)_2$ , corresponding to the acid  $\text{H}_3\text{SiO}_6(\text{H}_4\text{SiO}_4 + 2\text{H}_2\text{O})$ . The iron is partly replaced by magnesium and the aluminum by ferric iron.

**Blowpipe Tests.** Infusible.

Partially decomposed by  $\text{H}_2\text{SiO}_4$ .

**Occurrence.** 1. In mica schists often associated with cyanite, sillimanite, and garnet.

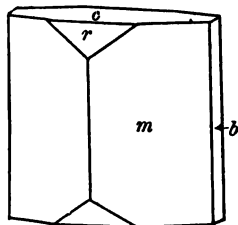


FIG. 579.



**Margarite,  $\text{H}_2\text{CaAl}_4(\text{SiO}_3)_2$** 

**Form.** Margarite is a micaceous mineral rarely found in well-defined crystals. Like the micas it occurs in lamellar forms and in scaly masses.

**Cleavage,** perfect in one direction.

**H.** = 4.

**Sp. gr.**  $\pm 3.0$ .

**Color,** gray, pink, white. Luster, pearly. Cleavage laminae are brittle, hence the name brittle mica sometimes used.

**Optical Properties.**  $n_g = 1.64$ . Cleavage flakes in convergent light give a negative biaxial interference figure with large axial angle ( $2E = 100^\circ - 120^\circ$ ).

**Chemical Composition.** Acid calcium aluminum silicate,  $\text{H}_2\text{CaAl}_4(\text{SiO}_3)_2$ ; ( $\text{H}_2\text{O} = 4.5$  per cent.).

**Blowpipe Tests.** Fusible at  $4\frac{1}{2}$  and whitens. In the closed tube yields water.

Partially decomposed by HCl.

**Occurrence.** 1. Associated with corundum and emery, probably as an alteration product. Chester, Massachusetts.

**CHLORITE,\*  $\text{H}_2(\text{Mg,Fe})_3\text{Al}_2(\text{SiO}_3)_3$** 

**Form.** Chlorite crystals are monoclinic but pseudo-hexagonal in habit, usually resembling crystals of the micas. The mineral also occurs in disseminated flakes and in scaly masses.

**Cleavage,** perfect in one direction.

**H.** = 2 to  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 2.8$ .

**Color,** green of various tints and shades, varying from almost white to almost black.

Cleavage laminae are flexible, but not elastic.

**Optical Properties.**  $n_g = 1.58$ . Fragments are irregular, green in color with faint pleochroism, and very low (often Berlin blue) first order interference colors. Cleavage flakes in convergent light

\* Chlorite is really the name of a group of minerals, but on account of the difficulty of distinguishing them they are all included under one heading.

give an interference figure which is either uniaxial, or biaxial with a small axial angle ( $2E = 0^\circ - 60^\circ$ ).

**Chemical Composition.** Acid magnesium-iron aluminum silicate. The composition varies for different chlorites; for one of them (clinochlore) the formula is  $H_8(Mg, Fe)_5Al_2(SiO_3)_3$ . In some varieties chromium and ferric iron partly replace the aluminum.

**Blowpipe Tests.** Fusible with difficulty ( $5\frac{1}{2}$ ). In the closed tube it gives about 12 per cent. of water at a high temperature.

Decomposed by  $H_2SO_4$ .

**Occurrence.** 1. A secondary mineral in igneous rocks, formed by the alteration of such silicates as biotite, hornblende, augite, etc.

2. In schists, often forming independent rock masses, the chlorite-schists.

### SERPENTINE, $H_4Mg_3Si_2O_9$

**Form.** Serpentine has never been found in crystals, though it often occurs pseudomorphous after other crystallized minerals. It is usually compact or granular massive, but also occurs in fibrous, columnar, and lamellar forms.

**H.** = 3, to 4.

**Sp. gr.**  $\pm 2.5$ .

**Color,** green of various tints and shades, from greenish-white to greenish-black. It is also often yellow, brown, or red and the color is not apt to be uniform, but is in spots and streaks.

**Optical Properties.**  $n_g = 1.57$ . Fragments are irregular, or prismatic or acicular with parallel extinction and positive elongation. The interference colors are low first order. The irregular fragments show aggregate structure between crossed nicols.

**Chemical Composition.** Acid magnesium silicate,  $H_4Mg_3Si_2O_9$ ; ( $H_2O = 12.9$  per cent.). Part of the magnesium is usually replaced by ferrous iron. Some analyses show a little aluminum and some a little calcium.

## Analyses of Serpentine

MgO	FeO	CaO	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	H <sub>2</sub> O	Misc.
42.6	0.1	0.1	.....	0.3	42.0	14.7	
36.5	1.9	.....	5.1	.....	42.9	13.2	NiO = 0.6
41.2	2.4	.....	.....	.....	41.3	14.5	
36.8	7.2	.....	2.6	.....	41.6	12.7	Cr <sub>2</sub> O <sub>3</sub> = tr.

**Blowpipe Tests.** Fusible with difficulty (6). In the closed tube gives water at a high temperature.

Decomposed by HCl.

**Uses.** Serpentine is used as an ornamental stone. Fibrous serpentine or chrysotile is one of the minerals included under the term *asbestos*, tremolite being the other.

**Occurrence.** 1. An alteration product of olivine and to a less extent of bronzite, forming the metamorphic rock serpentine from original peridotite.

2. A secondary mineral in seams and veins and on the border of serpentine rocks. *Chrysotile*, the fibrous variety, and *antigorite*, the lamellar variety, occur in this way.

3. An alteration product of diopside and olivine in crystalline limestones, thus forming the rocks known as ophicalcites.

Serpentine,  $H_4Mg_3Si_2O_{10}$ 

**Form.** Serpentine occurs in compact earthy masses, and occasionally in fibrous seams.

H. = 2 to 2½.

Sp. gr. ± 2.0.

**Color,** white, yellowish white, grayish white. Serpentine floats on water when dry.

**Optical Properties.** *n* about 1.54. Fragments are irregular with low first order interference colors and aggregate structure.

**Chemical Composition.** Acid magnesium silicate,  $H_4Mg_3Si_2O_{10}$ ; (H<sub>2</sub>O = 12.1 per cent.).

**Blowpipe Tests.** Fusible on thin edges (5). In the closed tube yields water. Heated with cobalt nitrate solution it becomes pink.

Gelatinizes with HCl.

**Uses.** Sepiolite or meerschaum is used for tobacco pipes.

**Occurrence.** 1. Associated with serpentine. (Asia Minor.)

### Kaolinite, $H_4Al_2Si_2O_9$

**Form.** Kaolinite is sometimes found in minute pseudo-hexagonal (monoclinic) crystals of tabular habit. Fig. 580 represents crystals found by the author at Argentine, Kansas, in a dolomitic limestone. The usual occurrence of kaolinite is in clay-like masses.

**H.** = 2 to  $2\frac{1}{2}$ .

**Sp. gr.**  $\pm 2.6$ .

**Color,** white, grayish, yellowish, etc.  
**Luster,** pearly to dull.

**Optical Properties.**  $n = 1.55$ . Fragments are irregular and show aggregate structure between crossed nicols.

**Chemical Composition.** Acid aluminum silicate,  $H_4Al_2Si_2O_9$ ; ( $H_2O = 14.0$  per cent.). Iron is often present in small amounts.

**Blowpipe Tests.** Infusible if pure. Heated with cobalt nitrate solution it becomes deep blue. In the closed tube gives water.

Insoluble in acids.

**Uses.** Kaolin, a mixture of kaolinite and other aluminum silicates with more or less quartz, feldspar, etc., is used in the manufacture of porcelain, china, and pottery.

**Occurrence.** 1. A secondary mineral formed from the feldspars either by carbonated water or by pneumatolysis. The association at some localities of kaolinite with fluorite and cassiterite proves its origin by pneumatolysis.

2. In sedimentary rocks formed by the alteration of aluminous silicates.

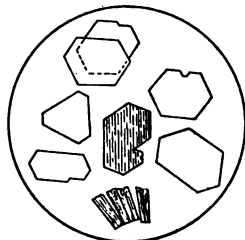


FIG. 580.  
Kaolinite crystals ( $\times 500$ ).

**Lawsonite,  $H_4CaAl_2(SiO_3)_2$** 

**Form.** Lawsonite usually occurs in tabular or prismatic orthorhombic crystals which are disseminated through the rock.

**Cleavage,** fair but not prominent.

**H.** = 8.

**Sp. gr.**  $\pm 3.1$ .

**Color,** white or gray.

**Optical Properties.**  $n_\gamma(1.68) - n_\alpha(1.66) = 0.02$ . Fragments are plates with parallel extinction or are irregular. The interference colors are bright.

**Chemical Composition.** Acid calcium aluminum silicate,  $H_4CaAl_2(SiO_3)_2$ ; ( $H_2O = 11.4$  per cent.).

**Blowpipe Tests.** Fusible to a blebby glass with exfoliation at first, but after that it is infusible and glows. In the closed tube it yields water at a high temperature.

Insoluble in HCl, but after fusion (alone) it gelatinizes.

**Occurrence.** 1. In glaucophane schists and related rocks. It has been formed from the anorthite molecule of plagioclase. Tiburon Peninsula, California is the type locality of lawsonite.

2. In gabbros and dionites as an alteration product of plagioclase.

**TITANITE,  $CaTiSiO_5$** 

**Form.** Titanite occurs in attached crystals, and in disseminated crystals and grains. Crystals are monoclinic of varied habit, but are usually acute rhombic in cross-section. Usual forms:  $c\{001\}$ ,  $m\{110\}$ ,  $n\{111\}$ . Interfacial angles:  $mm(110:\bar{1}10) = 66^\circ 29'$ ;  $nn(111:\bar{1}\bar{1}1) = 43^\circ 49'$ ;  $cm(001:110) = 65^\circ 30'$ ;  $cn(001:111) = 38^\circ 16'$ .

**Cleavage.** There is sometimes prominent parting in two directions at angles of  $54^\circ$ .

**H.** = 5 to  $5\frac{1}{2}$ .

**Sp. gr.**  $\pm 3.5$ .

**Color,** varying tints and shades of yellow and brown. **Luster,** adamantine or subadamantine.

**Optical Properties.**  $n_r(2.00) - n_a(1.88) = 0.12$ . Fragments are irregular and slightly pleochroic with very high order interference colors.

**Chemical Composition.** Calcium titanate-silicate,  $\text{CaTiSiO}_5$ , a salt of  $\text{H}_2\text{Si}_2\text{O}_5$  in which one atom of silicon is replaced by one of titanium.

**Blowpipe Tests.** Fusible at 4 to colored glass. Gives a violet  $\text{NaPO}_3$  bead in R.F.

Partially soluble in HCl.

**Occurrence.** 1. An accessory constituent of igneous rocks, very common and widely distributed.

2. In clefts and seams of metamorphic rocks.

3. Disseminated through metamorphic rocks and probably formed from titaniferous pyroxenes. Coast Ranges of California.

## E. HYDROUS SILICATES

Zeolite Group	APOPHYLLITE,	$(\text{H}, \text{K})_2\text{Ca}(\text{SiO}_3)_2 \cdot \text{H}_2\text{O}$
	HEULANDITE,	$\text{H}_2\text{CaAl}_2(\text{SiO}_3)_3 \cdot 3\text{H}_2\text{O}$
	STILBITE,	$\text{H}_4(\text{Na}_2, \text{Ca})\text{Al}_2(\text{SiO}_3)_6 \cdot 4\text{H}_2\text{O}$
	Laumontite,	$\text{H}_4\text{CaAl}_2(\text{SiO}_3)_7 \cdot 2\text{H}_2\text{O}$
	CHABAZITE,	$(\text{Ca}, \text{Na})_2\text{Al}_2(\text{SiO}_3)_4 \cdot 6\text{H}_2\text{O}$
	ANALCITE,	$\text{NaAl}(\text{SiO}_3)_2 \cdot \text{H}_2\text{O}$
	NATROLITE,	$\text{Na}_2\text{Al}_2\text{Si}_3\text{O}_{10} \cdot 2\text{H}_2\text{O}$
	Garnierite,	$\text{H}_2(\text{Ni}, \text{Mg})\text{SiO}_4 \cdot \text{H}_2\text{O}$
	Allophane,	$\text{Al}_2\text{SiO}_5 \cdot 5\text{H}_2\text{O}$
	CHRSYCOLLA,	$\text{CuSiO}_3 \cdot 2\text{H}_2\text{O}$

## ZEOLITE GROUP

Under the zeolites are included a number of hydrous silicates of aluminum with calcium and the alkalis, which are somewhat similar to the feldspars except for the water of crystallization. They are characterized by low specific gravity (2 to 2.5) and moderate hardness (3 to  $5\frac{1}{2}$ ).

They are all decomposed by HCl with the separation of slimy silica and are easily fusible (2 to 3) with intumescence, hence the name from the Greek word meaning to boil.

The zeolites are secondary minerals found in cavities of such basic igneous rocks as basalts and diabases. Table Mt. at Golden, Colorado, and Bergen Hill, New Jersey, are prominent localities for zeolites.

### APOPHYLLITE, $(\text{H,K})_2\text{Ca}(\text{SiO}_3)_2 \cdot \text{H}_2\text{O}$

**Form.** Usually occurs in distinct crystals in cavities and along seams. Apophyllite crystallizes in tetragonal crystals of varying habit. Usual forms:  $a\{100\}$ ,  $y\{310\}$ ,  $p\{111\}$ ,  $c\{001\}$ . Interfacial angles:  $cp(001:111) = 60^\circ 32'$ ;  $ap(100:111) = 52^\circ 0'$ ;  $pp(111:\bar{1}\bar{1}\bar{1}) = 76^\circ 0'$ ;  $ay(100:310) = 18^\circ 26'$ . (Figs. 581–584).

**Cleavage**, in one direction parallel to  $\{001\}$ .

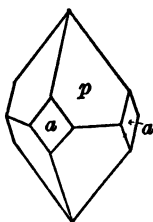


FIG. 581.

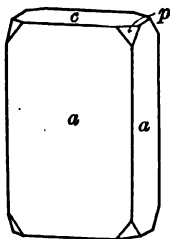


FIG. 582.

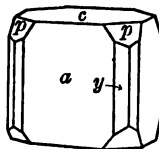


FIG. 583.

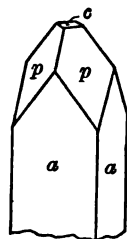


FIG. 584.

**H.** =  $4\frac{1}{2}$  to 5.

**Sp. gr.**  $\pm 2.3$ .

**Color**, colorless or white. **Luster** of (001) face, pearly; of other faces, vitreous.

**Optical Properties.**  $n_x(1.535) - n_z(1.533) = 0.002$ . Fragments are square or rectangular and are either dark between crossed nicols or have low first order interference colors. Cleavage flakes give a positive uniaxial interference figure in convergent light.

**Chemical Composition.** A hydrous acid calcium metasilicate,  $(\text{H,K})_2\text{Ca}(\text{SiO}_3)_2 \cdot \text{H}_2\text{O}$ . A little potassium replaces part of the hydrogen and some analyses show a little fluorin.

**Blowpipe Tests.** Easily fusible (2) with exfoliation to a white enamel. In the closed tube it yields water (about 16 per cent.).

Decomposed by HCl.

**Occurrence.** 1. In cavities of basic igneous rocks. West Paterson, New Jersey.

### HEULANDITE, $H_4CaAl_2(SiO_3)_6 \cdot 3H_2O$

**Form.** Heulandite crystallizes in the monoclinic system. Usual forms:  $b\{010\}$ ,  $c\{001\}$ ,  $t\{201\}$ ,  $s\{\bar{2}01\}$ ,  $m\{110\}$ . Angles:  $ct(001:201) = 63^\circ 40'$ ;  $cs(001:\bar{2}01) = 66^\circ 0'$ ;  $bm(010:110) = 68^\circ 2'$ . The habit is usually thick tabular parallel to  $\{010\}$ . The unsymmetrical outline of Fig. 585 is characteristic.

**Cleavage**, perfect in one direction parallel to  $\{010\}$ .

**H.** =  $3\frac{1}{2}$  to 4.

**Sp. gr.**  $\pm 2.2$ .

**Color**, colorless, white, pale brown, reddish. Luster pearly on the (010) face.

**Optical Properties.**  $n_\gamma(1.505) - n_\alpha(1.498) = 0.007$ . Fragments are plates with low first order interference colors. Cleavage flakes give a positive biaxial interference figure in convergent light.

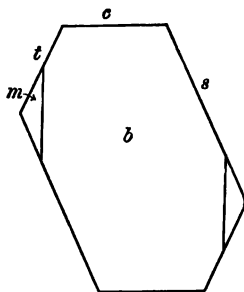


FIG. 585.

**Chemical Composition.** Hydrous acid calcium metasilicate,  $H_4CaAl_2(SiO_3)_6 \cdot 3H_2O$ ; ( $H_2O = 14.8$  per cent.). The calcium is usually partly replaced by small amounts of sodium, potassium, and strontium. Brewsterite is a similar isomorphous mineral with the calcium mostly replaced by strontium and barium.

**Blowpipe Tests.** Easily fusible (3) with exfoliation to a white enamel. In the closed tube it gives water.

Decomposed by HCl.

**Occurrence.** 1. A secondary mineral in cavities of basic igneous rocks.

### STILBITE, $H_4(Ca,Na_2)Al_2(SiO_3)_6 \cdot 4H_2O$

**Form.** Stilbite usually occurs in indistinct crystals or in sheaf-like aggregates. Crystals are monoclinic but are pseudo-



orthorhombic by twinning. The symmetrical outline of Fig. 586 is typical of stilbite.

**Cleavage**, in one direction rather perfect.

**H.** =  $3\frac{1}{2}$  to 4.

**Sp. gr.**  $\pm 2.1$ .

**Color**, white, yellow, brown.

**Optical Properties.**  $n_\gamma(1.500) - n_\alpha(1.494) = 0.006$ . Fragments are prismatic with parallel extinction and negative elongation.

The interference colors are upper first order.

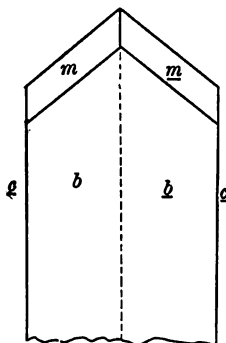


FIG. 586.

**Chemical Composition.** Hydrous acid calcium-sodium aluminum metasilicate,  $H_4(Ca, Na_2)Al_2(SiO_3)_6 \cdot 4H_2O$ ; ( $H_2O = 17.2$  per cent. if  $Ca:Na = 6:1$ ).

**Blowpipe Tests.** Easily fusible (3) with exfoliation to a white enamel. In the closed tube yields water.

Decomposed by HCl.

**Occurrence.** 1. A secondary mineral in cavities and seams of igneous rocks, especially basalts and diabases.

#### Laumontite, $H_4CaAl_2(Si_2O_7)_2 \cdot 2H_2O$ :

**Form.** Laumontite occurs in small crystals, and in fibrous and columnar forms. The crystals are monoclinic and prismatic in habit with acute terminations.

**Cleavage**, parallel to the length of the crystals.

**H.** = 3 to 4.

**Sp. gr.**  $\pm 2.3$ .

**Color**, white or reddish. Luster, somewhat pearly. Often crumbles on exposure.

**Optical Properties.**  $n_\gamma(1.525) - n_\alpha(1.513) = 0.012$ . Fragments are prismatic with low first order interference colors and oblique extinction ( $30^\circ$ ).

**Chemical Composition.** Hydrous acid calcium aluminum diorthosilicate,  $H_4CaAl_2(Si_2O_7)_2 \cdot 2H_2O$ ; ( $H_2O = 15.3$  per cent.).

**Blowpipe Tests.** Fuses at  $2\frac{1}{2}$  with swelling to a white enamel. In the closed tube it yields water.

**Occurrence.** 1. As a secondary mineral in igneous rocks, especially amygdaloidal basalts and diabases.

**CHABAZITE,  $(\text{Ca}, \text{Na}_2)\text{Al}_2(\text{SiO}_3)_4 \cdot 6\text{H}_2\text{O}$**

**Form.** Chabazite practically always occurs in distinct rhombohedral crystals which are cube-like ( $10\bar{1}1 : \bar{1}101 = 85^\circ 14'$  (Fig. 587). Penetration twins with  $c$  as the twin-axis are common.

**H.** =  $4\frac{1}{2}$ .

**Sp. gr.**  $\pm 2.1$ .

**Color,** white, colorless, pink, red.

**Optical Properties.**  $n_\gamma(1.488) - n_\alpha(1.485) = 0.003$ . Fragments are nearly square rhombs or are irregular. The interference colors are low first order.

**Chemical Composition.** Hydrous calcium-sodium aluminum metasilicate,  $(\text{Ca}, \text{Na}_2)\text{Al}_2(\text{SiO}_3)_4 \cdot 6\text{H}_2\text{O}$ . A little potassium is usually present.

**Blowpipe Tests.** Fuses at 3 with intumescence to a white glass. In the closed tube yields water (about 21 per cent.).

Decomposed by HCl.

**Occurrence.** 1. A secondary mineral in cavities and seams of igneous rocks associated with the other zeolites.

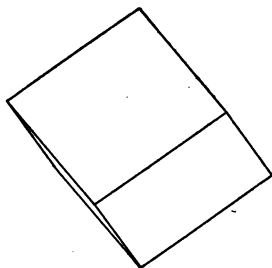


FIG. 587.

**ANALCITE,  $\text{NaAl}(\text{SiO}_3)_2 \cdot \text{H}_2\text{O}$**

**Form.** Analcite occurs in attached crystals or in druses lining cavities and seams. It is isometric in crystallization, the only common form being the trapezohedron,  $\{211\}$ , the same form that is common on garnet (Fig. 588).

**H.** = 5 to  $5\frac{1}{2}$ .

**Sp. gr.**  $\pm 2.2$ .

**Color,** colorless or white.

**Optical Properties.**  $n = 1.48$ . Isotropic. Fragments are irregular and dark between crossed nicols.

**Chemical Composition.** Hydrous sodium aluminum metasilicate,  $\text{NaAl}(\text{SiO}_3)_2 \cdot \text{H}_2\text{O}$ ; ( $\text{H}_2\text{O} = 8.2$  per cent.).

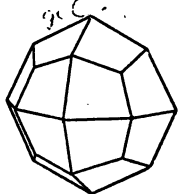


FIG. 588.

**Blowpipe Tests.** Fusible at  $3\frac{1}{2}$  to a colorless glass. In the closed tube gives water.

Soluble in  $\text{HCl}$  with gelatinization.

**Occurrence.** 1. A secondary mineral in seams and cavities of basic igneous rocks.

2. As an original constituent of certain diabases, called teschenites.

### NATROLITE, $\text{Na}_2\text{Al}_2\text{Si}_3\text{O}_{10} \cdot 2\text{H}_2\text{O}$

**Form.** This mineral occurs in divergent crystal groups or in fibrous masses. Crystals are orthorhombic but apparently tetragonal ( $110:1\bar{1}0 = 88^\circ 45'$ ). The habit is long prismatic or acicular terminated by the low bipyramid  $\{111\}$ .

Fig. 589 represents a typical natrolite crystal. The side face,  $b$ , proves it to be orthorhombic.

$H. = 5$ .

$Sp. gr. \pm 2.2$ .

**Color,** colorless or white.

**Optical Properties.**  $n_r(1.488) - n_a(1.475) = 0.013$ . Fragments are prismatic or acicular with parallel extinction, positive elongation, and bright interference colors.

**Chemical Composition.** Hydrous sodium aluminum silicate,  $\text{Na}_2\text{Al}_2\text{Si}_3\text{O}_{10} \cdot 2\text{H}_2\text{O}$ ; ( $\text{H}_2\text{O} = 9.5$  per cent.).

**Blowpipe Tests.** Easily fusible ( $2\frac{1}{2}$ ) to a colorless glass giving a yellow flame. In the closed tube it yields water.

Decomposed by  $\text{HCl}$  with gelatinization.

**Occurrence.** 1. A secondary mineral occurring in cavities of basalts and diabases.

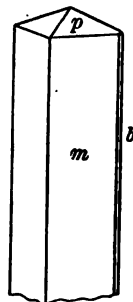
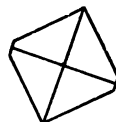


FIG. 589.

**Garnierite,  $H_2(Ni,Mg)SiO_4 \cdot H_2O$** 

**Form.** Garnierite has never been found in crystals. It occurs in earthy masses.

**H.** = 2 to 3.

**Sp. gr.**  $\pm 2.5$ .

**Color,** bright green to pale green.

**Optical Properties.**  $n$  about 1.59. Fragments are irregular, greenish in color, and show aggregate structure in polarized light.

**Chemical Composition.** A hydrous acid nickel-magnesium orthosilicate,  $H_2(Ni,Mg)SiO_4 \cdot H_2O$ .

**Blowpipe Tests.** Infusible. Heated on charcoal becomes magnetic. In the closed tube blackens and yields water. The borax bead is violet when hot.

Partially decomposed by HCl.

**Uses.** Garnierite is one of the chief ores of nickel. The French colony of New Caledonia is the only important locality.

**Occurrence.** 1. A secondary mineral associated with serpentinized peridotites; probably an alteration product of nickel-bearing olivine. Riddles, Oregon.

**Allophane,  $Al_2SiO_5 \cdot 5H_2O$** 

**Form.** Allophane is one of the very few amorphous minerals. It usually occurs in incrusting forms sometimes with a mammillary surface and resembles hyalite.

**H.** = 3.

**Sp. gr.**  $\pm 1.9$ .

**Color,** white, colorless, pale blue. Very brittle.

**Optical Properties.**  $n = 1.49$ . Isotropic. Fragments are irregular, colorless, and dark between crossed nicols.

**Chemical Composition.** Hydrous aluminum silicate,  $Al_2SiO_5 \cdot 5H_2O$ ; ( $H_2O = 35.7$  per cent.). Some varieties contain copper.

**Blowpipe Tests.** Infusible. In the closed tube gives a large amount of water at a low temperature. With cobalt nitrate solution it gives a deep blue color.

Soluble in HCl with gelatinization.

**Occurrence.** 1. A secondary mineral occurring in seams and incrustations.

### CHRYSOCOLLA, $\text{CuSiO}_3 \cdot 2\text{H}_2\text{O}$

**Form.** Chrysocolla is never found in crystals but occurs in seams and in incrustations, sometimes having a mammillary surface.

**H.** 2 to 4.

**Sp. gr.**  $\pm 2.1$ .

**Color,** bluish-green or greenish-blue.

**Optical Properties.**  $n$  about 1.57. Fragments are irregular, isotropic in part, but usually show aggregate structure in polarized light.

**Chemical Composition.** Hydrous copper metasilicate,  $\text{CuSiO}_3 \cdot 2\text{H}_2\text{O}$ ; (Cu = 36.1 per cent.,  $\text{H}_2\text{O}$  = 20.5 per cent.).

**Blowpipe Tests.** Infusible. Colors the flame green. In the closed tube it blackens and gives water.

Decomposed by HCl without gelatinization.

**Uses.** Chrysocolla is one of the so-called oxidized ores of copper.

**Occurrence.** 1. A secondary mineral often associated with malachite, azurite, and cuprite, and usually found in the upper workings of mines. Gila County, Arizona.

## PART VII

### THE OCCURRENCE, ASSOCIATION, AND ORIGIN OF MINERALS

#### 1. DISTRIBUTION AND OCCURRENCE

The earth's crust is composed, for the most part, of rocks which are made up of various minerals. Minerals forming the main bulk of rocks are comparatively few in number being limited to a dozen or so kinds, such as feldspars, pyroxenes, amphiboles, micas, olivine, quartz, and calcite. The great majority of minerals are found in rocks in small amounts, the so-called accessory constituents, or in veins, which are sometimes very rich in rare and valuable minerals, or as secondary minerals developed in cavities and other favorable places.

Some minerals are common in quantities the world over, for example, quartz, calcite, feldspars, pyrite, sphalerite, and hematite. Some are widely distributed but occur in small quantities, for example, zircon and titanite. Others occur in large quantities at a very few localities, for example: cryolite (West Greenland), franklinite (Sussex County, New Jersey) and carnallite (Stassfurt, Germany).

Minerals, unlike plants and animals, are not arranged in geographic zones, nor are they necessarily characteristic of any particular geological age except locally. The only zones that can be recognized are vertical zones depending upon physical conditions of temperature and pressure. Thus Van Hise recognizes three zones: (1) from the surface to the level of ground-water, (2) zone of ground-water, (3) zone below the ground-water.

Minerals occur in rocks or in mineral deposits such as veins, stockworks, contact deposits, etc. Rocks may be defined as

mineral aggregates which make up an essential part of the earth's surface. They are usually divided into three large groups, (1) igneous (those formed from fusions), (2) sedimentary (those laid down in water), and (3) metamorphic (original igneous or sedimentary rocks more or less modified by heat, pressure, or chemical action.) Though some minerals such as quartz and pyrite are common to all these groups, many are restricted in their occurrence. Leucite, for example, is found only in igneous rocks, while glaucophane is restricted to the metamorphic rocks.

## 2. ASSOCIATION AND ORDER OF SUCCESSION

The minerals of rocks and other mineral deposits occur together in more or less definite association one with another. Many of the associations are so characteristic that the experienced mineralogist makes use of the facts in determining minerals. On the other hand, the determination of minerals helps to decide the kind of rock or mineral deposit and so is important to the geologist, petrographer, and mining engineer. The following are some of the characteristic mineral associations: lepidolite, tourmaline, spodumene, beryl, and albite in granite-pegmatites; wolframite, cassiterite, scheelite, topaz, and fluorite in tin-stone veins; wollastonite, vesuvianite, wernerite, garnet, and calcite in limestone contacts; tremolite, phlogopite, chondrodite, spinel, and dolomite in crystalline dolomitic limestones; zeolites, calcite, datolite, prehnite, and apophyllite as secondary minerals in basic igneous rocks.

Not only the association but also the **order of succession** is often characteristic. In most granites the following order may be made out in a thin section: (1) magnetite, (2) biotite, (3) feldspar, and (4) quartz. In granites and igneous rocks generally, it is the solubility rather than the fusibility that governs the order of crystallization. Thus, quartz, though the most infusible, separates out last because it is most soluble under the given conditions.

In the Joplin lead and zinc district of south-west Missouri the minerals crystallizing free in cavities usually exhibit the following sequence: (1) dolomite, (2) galena, (3) sphalerite, (4) chalcopyrite, (5) marcasite, (6) calcite. In veins quartz is usually the first mineral to crystallize out, though it may also occur in a second generation. Minerals formed subsequent to the main rock mass are called **secondary**. For example, chalcedony in rhyolites, and cerussite in veins with galena, are secondary minerals.

### 3. ORIGIN OF MINERALS

Minerals may originate in various ways. Some have been formed from water solution (veins, spring deposits, secondary minerals in cavities) either by concentration of solutions or by chemical reactions. Some have been formed by separation from a molten magma (minerals of igneous rocks, such as granites, rhyolites, basalts, etc.). Others have been formed by organisms and still others by the chemical readjustment incident to metamorphism. To determine the method of formation and source of the material is an important part of mineralogical investigation.

Many minerals have been formed in several different ways and this fact is often indicated by a peculiarity of habit. Thus orthoclase is usually formed from fusion as in granites and rhyolites, but vein orthoclase (valencianite) has a pseudo-orthorhombic habit quite different from that found in igneous rocks.

### 4. PARAGENETIC VARIETIES

The present tendency in mineralogy is to do away with the old varietal names based upon non-essential properties and to substitute for them varieties based upon the mode of occurrence and possible origin. On account of the difficulty of always determining the origin it is convenient to base the varieties principally upon the mode of occurrence. **Paragenesis** is a term used for the association of minerals with special reference to their occurrence and origin. So these varieties may be designated by the term



**paragenetic varieties.** It is not possible to establish paragenetic varieties for all minerals at present and in many cases there may be a difference of opinion. The number of varieties also depends upon the subdivisions of rocks and mineral deposits used, which in turn depend upon the purpose in view. As an example of paragenetic varieties let us take the mineral calcite.

- (a) As a vein mineral, often as the gangue of metallic ores.
- (b) As travertine, calcareous tufa, and cave deposits.
- (c) As a biogenic mineral forming limestones.
- (d) As a secondary mineral in basic igneous rocks.
- (e) As a secondary mineral in seams and cavities of sedimentary rocks.
- (f) As the recrystallized material of crystalline limestones.

## 5. SYNTHESIS OF MINERALS

Besides filling up gaps in isomorphous groups and furnishing better material for study the synthesis of a mineral often gives a clue to its origin in nature. Most minerals have been produced artificially; even the diamond has been made in minute crystals in three or four different ways.

The methods of mineral synthesis differ greatly, the apparatus varying from a test-tube to the electric-furnace. A general method is that of the sealed tube. A hard glass tube containing the proper substances is sealed up and heated in a bomb furnace for several days or several weeks if necessary. Water vapor under pressure plays an important part in the reaction, as it also seems to in nature. An example of this method is the production of covellite ( $\text{CuS}$ ) by heating powdered sphalerite ( $\text{ZnS}$ ) in a water solution of  $\text{CuSO}_4$ , using an atmosphere of  $\text{CO}_2$ . After a few hours a blue black powder (covellite) appears. The reaction is  $\text{ZnS} + \text{CuSO}_4 = \text{CuS} + \text{ZnSO}_4$ . In the Joplin district the author has found covellite pseudomorphous after sphalerite, so that this reaction has doubtless taken place in nature. Geologic time is partly compensated for by increased temperature and pressure.

The basic igneous rocks are easily reproduced and such minerals

as olivine, pyroxene, leucite, and plagioclase crystallize out easily from a molten mass of the proper constituents.

French mineralogists and chemists have been especially active in mineral synthesis. The work of Fouqué and Lévy in mineral synthesis is a classic.

Intermediate between the naturally occurring minerals and the so-called artificial minerals are the minerals which have been formed on mine-tools, prehistoric implements, old coins, etc. Man has unintentionally furnished part of the material, but has not directed the conditions of the experiment, hence the term **accidental synthesis**. The author has identified cuprite, malachite, azurite, and cerussite on buried Chinese coins of the seventh century found at Kiukiang, China.

A classic example is that of the old Roman baths at the thermal springs of Bourbonne-les-Bains in France described by Daubrée. Here bronze coins thrown in the spring as votive offerings were incrustated with such minerals as chalcocite, chalcopyrite, bornite, and tetrahedrite. Zeolites were also formed in the conduits.

## 6. ALTERATIONS, PSEUDOMORPHS, AND REPLACEMENTS

Many minerals show evidences of **alteration**, especially around the border. The more common chemical changes involved are oxidation (sulfids to sulfates, sulfids to oxids, arsenids to arsenates, etc.), reduction (sulfates to sulfids, sulfids to metals, oxids to metals), and carbonation (sulfids to carbonates). There are also more complex changes which have received special names. The following may be mentioned as prominent alterations, many of them occurring as pseudomorphs: Galena to cerussite, sphalerite to smithsonite, pyrite to limonite, smaltite to erythrite, cuprite to malachite, olivine to serpentine (serpentinization), augite to hornblende (uralitization), and orthoclase to sericite, a variety of muscovite (sericitization).

A **pseudomorph** is one mineral with the form of another, a false form, as the name indicates. Thus limonite, which never crystallizes, is often found in cubes. As may be seen by breaking

water solutions. The minerals separate out in order of solubility rather than of fusibility. Thus in a granite composed of quartz, orthoclase, and biotite, quartz, the most infusible mineral, is the last to separate out.

The igneous rocks are classified on the basis of texture and occurrence, mineral components, and chemical composition. The following table gives the essential features of the commonly accepted classification. Thus syenite is a rock composed essentially of orthoclase (it may have small amounts of other minerals

Chemical composition	Acid SiO <sub>2</sub> , 80-65%	Intermediate SiO <sub>2</sub> , 65-52%		Basic SiO <sub>2</sub> , 52-40%	
VOLCANIC Texture porphyritic	Rhyolite	Trachyte	Andesite	Basalt	(rare)
PLUTONIC Texture granular	Granite	Syenite	Diorite	Gabbro	X Peridotite
Essential Minerals	Orthoclase		Plagioclase		No feldspars
			Hornblende	Pyroxene	
	Quartz				Olivine

also) without quartz, has granular texture, has a moderate silica percentage, and occurs in deep-seated masses. As rocks are mixtures of minerals the definite lines of the classification do not exist in nature. Rocks intergrade in all directions and many are difficult to classify.

There is good evidence to show that some rocks are the result of a splitting up of an original magma into several magmas. This process is known as **magmatic differentiation**. These separate magmas are characterized by differences in the minerals or by differences in the chemical composition. Some ores such as magnetite, ilmenite, and chromite are supposed to have originated in this way. These ores are considered to be ultra-basic rocks

formed by segregation of the metals from a large rock mass while in the form of a magma.

### 8. VOLCANIC EXHALATIONS

Among the gases given off by volcanoes and fumaroles are  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ,  $\text{H}_2\text{S}$ ,  $\text{SO}_2$ , and  $\text{HCl}$ . These, reacting upon each other and upon the minerals of the surrounding rocks, give rise to such minerals as sulfur, sylvite, sal-ammoniac, gypsum, sassolite ( $\text{H}_3\text{BO}_3$ ), and hematite, minerals which crystallize in the pores of the lava. Hematite is formed thus:  $2\text{FeCl}_3 + 3\text{H}_2\text{O} = \text{Fe}_2\text{O}_3 + 6\text{HCl}$ . Vesuvius is a prominent locality for a great variety of minerals which have been formed in this way.

In burning coal mines and coal-mine dumps, such minerals as sulfur, sal-ammoniac, orpiment, and realgar are sometimes formed by sublimation.

### 9. PEGMATITES

Pegmatites are dikes or veins that have been formed during the last stages in the consolidation of plutonic rocks through the agency of mineralizers or dissolved vapors. They probably represent a residual mother liquor which has been injected into fissures. Among the characteristics of pegmatites are large crystals, simultaneous crystallization of minerals, variability in different parts of the vein, and the presence of rare elements and unusual minerals. There are pegmatites corresponding to most of the known plutonic rocks, but they are especially prominent in granites. In this country granite-pegmatites are prominent in New England, in South Dakota (Black Hills), and in San Diego County, California. The following are the characteristic minerals of granite-pegmatites: quartz, orthoclase, albite, muscovite, lepidolite, tourmaline, spodumene, amblygonite, topaz, beryl, and columbite. In Norway gabbro-pegmatites contain apatite, rutile, ilmenite, hornblende, and wernerite. In southern Norway a host of rare minerals has been found in the nepheline-syenite pegmatites.

## 10. CLASTIC ROCKS

The clastic rocks are those which are made up of fragments of preexisting rocks, usually more or less sorted by water. They may be distinguished from igneous rock by their fragmental nature, banded appearance, and often by the presence of fossils.

**Tuffs** are fragmental igneous rocks formed by the explosive action of volcanoes and are often interbedded with lavas. They are composed of angular fragments of glass and of rock-fragments. They are named according to the rock to which they correspond, rhyolite-tuffs, andesite-tuffs, etc.

Clays, sand, and gravel are, in a geological sense, unconsolidated rocks. **Clays** are made up principally of hydrated silicates such as sericite and kaolinite, as well as of minute fragments of quartz and feldspars. The most prominent mineral of **sands** and **gravels** is quartz, but it may be accompanied by such minerals as feldspars, garnet, and magnetite. Locally almost any mineral may be found in a sand. On the Hawaiian beaches the sand is largely olivine from the decomposing basalt.

Shales, sandstones, conglomerates, breccias, and limestones are the common consolidated clastic rocks. They are consolidated partly by the pressure of overlying rocks and partly by the cementing material which is usually calcite, quartz, chalcedony, or limonite. **Shales** are consolidated clays with the same minerals as the latter. **Sandstones** are consolidated sands with quartz as the prominent mineral. A feldspathic sandstone is called an **arkose**. A **conglomerate** is a consolidated gravel made up of rounded pebbles, while in a **breccia** the pebbles are more or less angular. Quartz is the most prominent mineral of conglomerates and breccias. Limestones are, as a rule, due to the accumulation of organic remains such as shell fragments, crinoid stems, etc., and have been comminuted so as to form a calcareous mud.

The clastic rocks are usually porous, hence percolating solutions carrying dissolved mineral matter often deposit minerals

in clefts, seams, and other cavities. The principal secondary minerals so formed are calcite, dolomite, barite, aragonite, quartz, chalcedony, gypsum, pyrite, and vivianite.

## 11. ORGANIC DEPOSITS

The principal example of a rock formed by organisms is **limestone**. Molluscs, brachiopods, corals, crinoids, and other animals secrete calcium carbonate from the sea-water to form shells and other external skeletons. The calcium carbonate recrystallizes to form calcite or in some cases aragonite. Silica, principally in the form of opal, is secreted by sponges, radiolaria, and diatoms. Probably some chert is formed by the recrystallization of silica in the form of chalcedony. A variety of opal called geyserite is also secreted by the algæ of certain hot springs. Limonite is formed in part by organisms. Sulfur is sometimes produced by certain bacteria from sulfate bearing waters. Niter is produced by bacteria from ammonia and other nitrogenous substances such as guano. The Chili saltpeter deposits have perhaps been formed in this way and then have been recrystallized.

## 12. VEINS

Under favorable conditions of temperature and pressure almost all inorganic substances are soluble in certain kinds of water. Silica is soluble in heated alkaline water. Water charged with carbon dioxid will dissolve carbonates. Sulfids are soluble in alkaline waters. Most **veins** are supposed to have been produced by the opening of narrow fissures, due principally to faults, and by the subsequent filling of the fissures. Percolating solutions would deposit minerals either by simple concentration or by reactions with other solutions whereby precipitates are formed. The effect of crystallization would tend to widen the vein.

Veins differ greatly in width and extent. Some are known to continue downward for 3,000 feet. In the Hartz Mts., Germany, veins have been traced for ten miles, but these are exceptional

cases. Veins usually possess a banded structure and are more or less symmetrical, the symmetry being due to the fact that the solutions deposited their contents equally on both walls of the fissure. Fig. 590 illustrates a symmetrical vein from Freiberg. Fig. 591 is a drawing of a tin-stone vein from Zinnwald. A broad zone of rock with narrow more or less parallel anastomosing veins is known as a **lode**, though some writers use *lodé* as a synonym of vein.

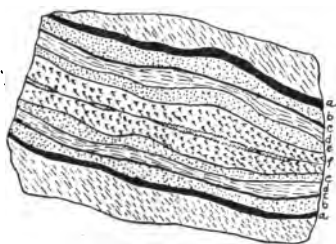


FIG. 590.—Vein (after von Weissenbach). a, c, sphalerite; b, e, fluorite; d, barite; f, calcite.

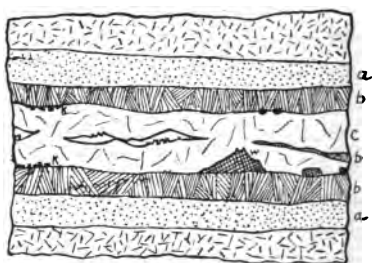


FIG. 591.—Tin-stone vein (after Beck). a, greisen; b, lepidolite; c, fluorite; k, cassiterite; w, wolframite.

The principal **gangue minerals** of veins are quartz, calcite, dolomite, siderite, rhodochrosite, fluorite, and barite. The principal **ore minerals** are pyrite, chalcopyrite, sphalerite, galena, arsenopyrite, tetrahedrite, argentite, ruby silvers, and gold.

The exposed oxidized portion of a vein or lode is known as a **gossan** or "iron-hat." Gossans are usually more or less cellular rusty outcrops which extend to varying depths. The minerals of a gossan are mostly secondary and are usually oxidation products of the original sulfids of the vein. Among the prominent minerals may be mentioned limonite, hematite, cerussite, anglesite, malachite, azurite, cuprite, copper, chrysocolla, smithsonite, calamine, cerargyrite, silver, and gold. There is often a concentration of the precious metals in the gossan.

In a zone between the gossan and the unaltered sulfids such minerals as chalcocite, covellite, bornite, and the ruby silvers are often found. This deposit constitutes a zone of **secondary sulfid enrichment** and results from reactions between the sulfates of the gossan (in solution) and the unaltered sulfids below.

### 13. SPRING, LAKE, AND SEA DEPOSITS

**Calcareous tufa** and **travertine** are banded deposits of calcium carbonate formed around springs and in limestone caverns as the result of the evaporation of carbonated water holding calcium carbonate in solution. Cave-deposits such as stalactites and stalagmites belong to the same category.

The evaporation of ocean water in closed inland seas gives rise to beds of rock-salt, gypsum, and anhydrite and in exceptional cases as at Stassfurt, Germany, to such minerals as carnallite and polyhalite. Sylvite and kainite are secondary minerals in the Stassfurt deposits.

The borax and soda lakes of the arid regions of California and Nevada furnished on evaporation borax, ulexite, hanksite, the-nardite, and similar minerals. The source of the boracic acid is unknown. Among other minerals formed in the lakes of arid regions are trona from Owens Lake, California, mirabilite from Great Salt Lake, Utah, and epsomite from lakes in Albany County, Wyoming.

### 14. METAMORPHIC ROCKS

Certain prominent rocks which will not fall in any of the preceding divisions are called metamorphic rocks. They are usually more or less banded crystalline rocks which have been formed from igneous or sedimentary rocks by recrystallization due either to the heat of an igneous intrusion, or to the pressure resulting from mountain-making.

The metamorphism due to igneous intrusion is called **contact metamorphism** because the effects, though often striking, are



confined to the immediate vicinity of the intruded mass. By **contact metamorphism** an impure siliceous limestone becomes a crystalline limestone with new silicate minerals. Shales are changed to a dark compact rock called hornfels. Bituminous coal or lignite may be changed to anthracite or even to coke.

Contrasted with contact metamorphism is **regional metamorphism** by which rock-masses over large areas are affected. By regional metamorphism shales become slates; limestones, marbles; sandstones, quartzites; while schists and gneisses are produced from various kinds of rocks.

**Schists** or finely laminated metamorphic rocks contain muscovite, biotite, chlorite, hornblende, actinolite, glaucophane, talc, quartz, and garnet. They are named according to a prominent constituent as hornblende schist, chlorite schist, etc.

**Gneisses** are coarsely banded rocks grading into the schists. They contain the same minerals as the schists except that the feldspars are more prominent.

**Quartzites** are metamorphic sandstones with a firm siliceous cement of quartz or chalcedony so that on fracture the grains are broken through as well as the cement.

**Slates** are dark-colored, fine-grained metamorphic rocks derived from shales. New rock cleavage, which has no relation to the original bedding plane, has been developed and is called slaty cleavage. The minerals of slates, as far as they can be recognized, are quartz, chlorite, muscovite, pyrite, and andalusite. The dark color is due to carbonaceous matter.

**Crystalline limestones** are developed from ordinary limestones by metamorphism. If the original limestone was pure it is simply a case of recrystallization, large anhedra of calcite often forming. The characteristic minerals of crystalline limestones are calcite, wollastonite, garnet, vesuvianite, graphite, and diopside. In the dolomitic or magnesian limestones calcite, dolomite, tremolite, phlogopite, chondrodite, graphite, and spinel are found. These minerals with the exception of calcite and dolomite are formed from the impurities of the original limestone.

**Serpentines** are altered peridotites (basic plutonic igneous rocks composed essentially of olivine and some variety of pyroxene). The mineral serpentine has been derived from olivine principally, according to the equation  $2\text{Mg}_2\text{SiO}_4 + \text{CO}_2 + 2\text{H}_2\text{O} = \text{Mg}_3\text{H}_4\text{Si}_2\text{O}_9 + \text{MgCO}_3$ . The prominent minerals in serpentine are olivine (original), pyroxene (original), chromite, magnetite, magnesite, hydromagnesite, dolomite, aragonite, brucite, opal, and the mineral serpentine found in seams as well as in the main rock mass.

## 462 INTRODUCTION TO THE STUDY OF MINERALS

## Mineral Products of the United States

(Amounts over \$100,000 in round numbers according to the United States Geological Survey)

	1910	1911	1912	1913
Coal.....	\$629,557,000			
Pig iron.....	425,115,000			
Clay products.....	170,116,000			
Copper.....	137,180,000			
Petroleum.....	127,896,000			
Gold.....	96,269,000			
Stone.....	76,520,000			
Natural gas.....	70,756,000			
Cement.....	68,752,000			
Lead.....	32,756,000			
Silver.....	30,854,000			
Zinc.....	27,268,000			
Sand.....	19,521,000			
Lime.....	13,895,000			
Phosphate rock.....	10,917,000			
Aluminum.....	8,956,000			
Salt.....	7,900,000			
Gypsum.....	6,523,000			
Mineral waters.....	6,357,000			
Slate.....	6,237,000			
Zinc oxid.....	5,325,000			
Sulfur.....	4,605,000			
Asphalt.....	3,080,000			
Mineral paints.....	2,175,000			
Glass sand.....	1,517,000			
Antimonial lead.....	1,338,000			
Borax.....	1,202,000			
Sand-lime brick.....	1,169,000			
Quicksilver.....	958,000			
Pyrite.....	958,000			
Talc and soapstone.....	864,000			
Tungsten ores.....	807,000			
Grindstones.....	796,000			
Fibrous talc.....	728,000			
Bauxite.....	716,000			
Feldspar.....	502,000			
Fluorspar.....	430,000			
Graphite.....	377,000			
Mica.....	337,000			
Precious stones.....	296,000			
Fuller's earth.....	294,000			
Oilstones, etc.....	229,000			
Quartz.....	194,000			
Manganiferous ores.....	187,000			
Peat.....	140,000			
Infusorial earth.....	130,000			
Barite.....	122,000			
Garnet.....	113,000			
Miscellaneous.....	806,000			
Total.....	\$2,003,745,000			

## **PART VIII**

### **THE USES OF MINERALS**

The magnitude of the mineral industry of this country may be appreciated by a perusal of the table on the opposite page, giving the value of the mineral products for the year 1910 (blank spaces are provided for subsequent years). The total value reaches a little over two billion dollars.

In this discussion of economic mineralogy the minerals are grouped in three classes: (A) Those used in the natural state (after concentration if necessary), (B) those used for the extraction of metals and alloys, and (C) those used in the chemical industries. Under the various heads the chief minerals, the producing localities, the treatment, uses, and production are given. Coal, petroleum, gas, clay products, cement, and stone are not treated as they are not definite minerals.

#### **A. MINERALS USED IN THE NATURAL STATE**

The minerals used in the natural state are discussed in the following order: Precious stones, ornamental stones, abrasives, refractory materials, glass, porcelain, and pottery, paints and graphic materials, fertilizers, fluxes, lubricants, paper-making materials, plaster, mica, and sulfur.

##### **1. PRECIOUS STONES**

The qualities that make minerals valuable as precious stones are color, luster, dispersion, and hardness. Precious stones are sold by the carat, which is equal to about 205 milligrams. The proposed metric carat is 200 milligrams.

The four great gems that rank above all the others are diamond, emerald, ruby, and sapphire.

**Diamond.** Diamonds were first obtained in India, and later Brazil furnished the main supply, but in recent years the Kimberley mines in South Africa have supplied about 95 per cent. of the total output of the world. In South Africa diamonds occur in a peculiar serpentine breccia known as "blue ground," which fills what appears to be volcanic necks. The diamond bearing rock is allowed to weather for some time and then the material is concentrated by means of greased shaking tables, the diamonds alone adhering.

In Brazil, India, and most other localities, diamonds occur in alluvial sands and gravels. In the United States diamonds have been found in the glacial drift of Wisconsin, Michigan, and Illinois and in placer-deposits in California and North Carolina.

Recently diamonds have been discovered in Pike County, Arkansas, in a decomposed peridotite somewhat like that of South Africa. About a thousand stones in all have been found and some of them are of very fine quality.

**Emerald** is a deep green variety of beryl. A flawless emerald is very rare and commands a far higher price than a diamond, a one-carat stone bringing over \$1000. Colombia, South America, is the principal locality for the emerald.

**Ruby** is a deep red variety of corundum and like the emerald is considered more valuable than the diamond. A few have been found in North Carolina, but the finest ones come from Burma.

**Sapphire** is the blue transparent variety of corundum. Ceylon and Siam have furnished the principal supply, but they have also been found at several localities in North Carolina and Montana. At Yogo Gulch, Montana, sapphires and other varieties of corundum occur disseminated through a dike of basic igneous rock, which is exposed on the surface for over four miles.

Varieties of corundum other than ruby and sapphire are distinguished by the prefix oriental. Thus oriental emerald is green corundum and oriental amethyst, purple corundum, etc.

**Spinel.** An intense red variety known as ruby-spinel is the principal one used as a gem. It is found in Ceylon and Burma.

**Hiddenite** is an emerald green variety of spodumene found in North Carolina.

**Kunzite** is a lilac colored variety of spodumene found in the pegmatites of San Diego Co., Cal. It was named in honor of Dr. George F. Kunz, the leading gem expert in this country.

**Tourmaline.** Pink, red, and green varieties of tourmaline suitable for gems are found in San Diego Co., Cal., and in Maine and Connecticut. They occur in pegmatites associated with beryl, topaz, and kunzite.

**Chrysoberyl.** There are several varieties used as gems, the cat's-eye with opalescent striations, and alexandrite, which is green by daylight and red by artificial light.

**Zircon.** Zircon occurs in a variety of colors and some are used as gems. The red and orange varieties are called hyacinth and the colorless, smoky, or yellowish varieties, jargon. They are found in the gem-bearing gravels of Ceylon.

**Garnet.** Both pyrope and almandite are used as gems as well as some rare varieties. A purplish-red variety known as rhodolite occurs in North Carolina. The ordinary gem garnet is pyrope. It is extensively mined in Bohemia.

**Turquoise.** The best quality of turquoise is obtained from Persia, but at present the United States furnishes the principal supply. Turquoise is found in the Los Cerillos Mts. and the Burro Mts. of New Mexico and also at various localities in Arizona and California.

**Topaz** is found in the Urals, in Brazil, in the Thomas Mts., Utah, and in San Diego Co., California.

**Beryl.** Besides emerald the gem varieties include golden beryl, pink beryl, and aquamarine, a pale bluish-green stone. Pink beryl and aquamarine are found in San Diego Co., California. Rose colored beryl of gem quality recently found in Madagascar has been named morganite.

**Olivine.** The gem variety is known as peridot. Peridot has

been found at several localities in northern Arizona, occurring in a peridotite.

**Opal.** Precious opal is found in New South Wales and in Hungary and fire-opal in Mexico. At all of these localities opal occurs as a secondary mineral in volcanic rocks.

**Minor Gems.** Among minor gems may be mentioned epidote, lapis-lazuli, moonstone (a variety of feldspar), iolite, diopside, vesuvianite, andalusite, cyanite, staurolite, axinite, benitoite, and numerous varieties of quartz and chalcedony such as amethyst, rose quartz, smoky quartz (called smoky topaz), chrysoprase, moss-agate, and bloodstone.

*Domestic Production of Precious Stones.* The production of precious stones in the United States for 1910 amounted to \$296,000, in the following order: turquoise (\$86,000), sapphire (\$53,000), tourmaline (\$46,000), kunzite (\$33,000) variscite, a hydrous phosphate of aluminum from Utah (\$26,000), chrysoprase (\$9,000), and californite (\$8,000).

Contrast this amount with the imports into the United State. which amounted in 1910 to about \$43,000,000, mostly diamonds.

## 2. ORNAMENTAL STONES

The following minerals are used extensively for vases, table-tops, mantels, and other interior decorations.

**Jade** is a valuable ornamental stone, consisting either of a variety of actinolite or tremolite called nephrite or of a distinct mineral of the pyroxene group called jadeite. It is a compact, very tough material of a green color and is highly prized by the Chinese. Jade has not been found in this country, but a related substance called **californite**, a compact variety of vesuvianite, has been discovered at several localities in California. The production of californite in 1910 was about \$8,000.

**Serpentine**, a compact mottled or streaked rock of various shades of green is used for mantels, wainscotings, and the like. It is quarried in Vermont, Pennsylvania, and Washington.

**Malachite** from the Urals is used extensively in Russia.

**Rhodonite**, also from the Urals, is a favorite ornamental stone in Russia.

**Lapis-lazuli**, a mixture of lazurite, calcite, pyrite, amphibole, and diopside, found in Persia, India, and other localities is a much valued ornamental stone known in ancient times.

**Mexican onyx** or onyx marble is a banded variety of calcite or aragonite formed from water solutions. Mexican onyx is found in Arizona and California, but the principal supply comes from Mexico. It is used for interior decorations such as soda fountains.

**Alabaster** is a translucent variety of gypsum used for statuary. The alabaster of antiquity was onyx marble.

**Marble** exceeds all the other ornamental stones in amount and value. It is quarried principally in Vermont and Tennessee, though large deposits are known in other states.

**Verde-antique** or ophealcite is crystalline limestone with mottlings or streaks of serpentine. Vermont is the principal source.

**Chalcedony**. Silicified wood is made into polished slabs for table-tops.

### 3. ABRASIVES

**Corundum**. Canada is the principal producer of corundum. In the vicinity of Craigville, Ontario, corundum occurs in syenite. The rock is crushed and the impurities removed by washing and scouring. North Carolina and Georgia have been the only domestic producers. The domestic production in 1910 together with that of emery amounted to only 1,000 short tons, valued at \$15,000.

**Emery** is an intimate mechanical mixture of corundum and magnetite or hematite, sometimes also with spinel. Emery is obtained chiefly in Asia Minor, and on the island of Naxos in the Grecian Archipelago. Chester, Massachusetts, and Peekskill, New York, have produced some emery.

**Garnet** as an abrasive is mined principally in Warren County,



New York. It is crushed and used as garnet sand-paper for dressing wood and leather. In 1910 the domestic production was 3,800 short tons, valued at \$113,000.

**Quartz.** Crystalline vein quartz is used in various industries as an abrasive material.

**Diamond.** Diamond powder is used as abrasive in cutting and polishing gems.

A black, almost opaque variety of diamond called **carbonado** is the most valuable abrasive known. It is used extensively in diamond drills. A large well-set diamond drill is worth about \$10,000. Carbonado is found only in Bahia, Brazil, as a constituent of sands and gravels. It is harder than the gem diamond, and is worth as much per carat as the ordinary straw yellow diamond.

**Other Abrasives.** Among other abrasives are whetstones and grindstones in the production of which Ohio leads; millstones and buhrstones used in grinding cereals, paints, and other mineral products; diatomaceous earth, a porous material composed of the siliceous remains of diatoms; volcanic ash, a fine comminuted natural glass; tripoli, a decomposed chert found in southwestern Missouri; flint-pebbles, used in tube-mills for fine grinding of ores.

Artificial abrasives include carborundum, a silicon carbide,  $\text{SiC}$ , made in the electric furnace at Niagara Falls, by fusing together silica, coke, and sawdust, and alundum, artificial  $\text{Al}_2\text{O}_3$ , made in the electric furnace from bauxite.

#### 4. REFRACTORY MATERIALS

The following minerals are used as furnace linings, covering for boilers and steam-pipes, and as fire-proof building materials.

**Asbestos.** There are two different minerals known as asbestos, one a fibrous tremolite and the other fibrous serpentine or chrysotile. The chrysotile is the stronger of the two, but has a shorter fiber. Asbestos is either used by itself or mixed with magnesia, saw dust, Portland cement, etc., and is made into rope, cloth, boards, and blocks. Canada leads in the production of as-

bestos. Georgia is the principal domestic producer. In 1910 the production in the United States amounted to 3700 short tons valued at \$68,000. The imports, on the other hand, amounted to about a million dollars.

**Talc.** The massive variety known as steatite or soapstone is sawed into slabs and used for stove-linings, washtubs, switchboards, laboratory tables, etc. Virginia is the principal producer. In 1910 the domestic production was 79,000 short tons valued at \$864,000.

**Graphite** is used in the manufacture of crucibles, being mixed with clay and sand. Austria and Ceylon lead in the production. In 1910 the domestic production was 51,000 short tons valued at \$377,000. The imports were about six times that amount.

**Diatomaceous earth** is a good non-conductor of heat on account of its porous nature.

**Chromite, calcined magnesite, and bauxite** are used in the manufacture of bricks for furnace linings.

## 5. GLASS, PORCELAIN, AND POTTERY

The minerals mentioned are used either for the body of the ware or for the glaze.

**Feldspar.** Orthoclase or microcline is used in the manufacture of porcelain and chinaware. It is obtained principally from pegmatites in Maine, Pennsylvania, and Connecticut. The domestic production in 1910 was 81,000 short tons valued at \$502,000.

**Quartz** is mixed with feldspar in the manufacture of porcelain. It is obtained in pegmatites along with feldspar.

**Glass Sand.** Sand, or sandstone nearly free from iron, is used in the manufacture of glass, the other constituents being soda-ash and limestone. Pennsylvania leads in the production. In 1910 the domestic production was 1,461,000 short tons valued at \$1,517,000.

**Fluorite** is used to some extent in the manufacture of opalescent glass and enamel.

**Halite** furnishes the glaze of pottery.

**Clays** are used extensively in the manufacture of pottery. Pottery to the value of \$33,784,000 was produced in the United States in 1910.

## 6. PAINTS AND GRAPHIC MATERIALS

**Graphite** is used in the manufacture of lead pencils, being mixed with clay to form various grades of hardness; also as stove polish and as an exterior paint.

**Hematite.** The Clinton iron ore and other varieties of hematite made into metallic paint are used for bridges, roofing, etc.

**Ocher, umber, and sienna** are earthy varieties of limonite and hematite mixed with clay and other impurities. They are washed, floated, ground, and sometimes roasted, producing a variety of colors. In 1910 the domestic production was 13,000 short tons valued at \$139,000.

**Barite**, finely ground and floated, is extensively used as a basis of paint and also as an adulterant of white lead. The leading supply comes from southeastern Missouri. In 1910 the domestic production was 43,000 short tons valued at \$122,000.

**Talc and pyrophyllite** are used as tailor's chalk, crayons, and slate pencils.

## 7. FERTILIZERS

Nitrates, phosphates, and potassium are essential to plant growth, hence the use of the following minerals to replenish these constituents in soils.

**Apatite.** In Norway and Canada extensive deposits of apatite occur and are mined to some extent. In the United States apatite is recovered as a by-product in the magnetic separation of magnetite in the iron-ore at Mineville, N. Y.

**Phosphate Rock.** The impure calcium phosphate known as phosphate rock is mined principally in the southern states, Florida, Tennessee, and South Carolina being the leading producers. According to the occurrence the phosphates are classed as hard rock, land pebble, and river pebble. There are

recent discoveries of extensive deposits of phosphate rock in the area where Idaho, Wyoming, and Utah join. It occurs as a dark colored oölitic rock interbedded with shales, sandstones, and limestones of Upper Carboniferous age. To render the phosphate available for plant food phosphate rock must be treated with sulfuric acid. This is the principal use of sulfuric acid. The domestic production in 1910 was 2,655,000 long tons valued at \$10,917,000. In the world's production the United States is first, followed by Tunis.

**Potassium salts** used as fertilizers are obtained from Stassfurt, Germany. The principal minerals used are kainite and carnallite.

**Nitrates.** The chief source of nitrates is sodium nitrate or Chili saltpeter from the desert regions of northern Chili, where there are extensive deposits.

Norwegian saltpeter or calcium nitrate is now made by fixing the nitrogen of the air. Nitric oxid formed at the high temperature of the electric arc is passed into calcium hydroxid solution and calcium nitrate is the result. Calcium cyanamid,  $\text{CaCN}_2$ , is another compound with available nitrogen that is made from the air. Nitrogen, made either by the fractional distillation of liquid air or by passing air over heated copper, is heated with calcium carbid to a temperature of  $1100^\circ \text{C}$ ., when calcium cyanamid is the result. Calcium nitrate and cyanamid plants are located in Norway, Italy, and Dalmatia at localities where cheap electric power can be generated by waterfalls.

**Ammonium sulfate**, a by-product in the manufacture of coal-gas, is also a valuable fertilizer.

**Gypsum** or land plaster is used as a fertilizer, especially in arid regions to neutralize black alkali or sodium carbonate.

## 8. FLUXES

In smelting ores it is necessary to add certain constituents to help in the reduction and to combine with impurities to form fusible slags.

**Limestone** is the principal flux used in this country. It is used with siliceous ores of various kinds and also with iron ores.

**Fluorite** is a valuable flux, especially in iron-smelting and in foundry work. Southern Illinois and western Kentucky furnish the principal supply. In 1910 the domestic production was 69,000 short tons valued at \$430,000. A good deal of fluorite is imported from England.

**Quartz.** Silica in the form of quartzite or low grade siliceous ores is used as an acid flux with basic ores.

**Manganiferous iron-ores** are used as a flux in some smelters. Leadville, Colorado, has supplied a notable amount.

## 9. LUBRICANTS

Graphite, talc and mica are the principal lubricants used for machinery. Their value lies in their foliated character, in their ability to stand high temperatures, and in the fact that they fill in irregularities.

## 10. PAPER-MAKING MATERIALS

Barite, magnesite (calcined), clay, and fibrous talc are used in paper-making. Fibrous talc is especially desirable on account of the strength that the fibers impart to paper. This product, called agalite, is mined extensively in St. Lawrence Co., N. Y. In 1910 the domestic production was 71,700 short tons valued at \$728,000.

## 11. PLASTER

**Gypsum** is now used principally in the manufacture of plaster. The rock gypsum is finely ground, calcined so as to drive off a part of the water, and then ground again. Various foreign substances such as glue, hair, or fine wood shavings, called retarders are added to prevent quick setting. Plaster is  $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ , but on mixing with water and setting, it becomes gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) again.

The United States and France are the world's principal producers of gypsum. In the United States the states in order of production are New York, Iowa, Michigan, and Oklahoma. The domestic production in 1910 was 2,239,000 short tons valued at \$6,523,000.

## 12. MICA

Large quantities of mica are used as an insulating material in the electrical industry. There are many minor uses. India, Canada, and the United States rank first in the production of mica. North Carolina and South Dakota furnish the principal domestic supply which in 1910 amounted to 2,476,000 pounds of sheet mica and 4,000 short tons of scrap mica, together valued at \$337,000.

## 13. SULFUR

The world's principal supply of sulfur is derived from Sicily. In the United States the largest deposit is a bed of sulfur over 100 feet thick in Calcasieu Parish, Louisiana. On account of the difficulty of sinking a shaft the sulfur is obtained by forcing superheated steam down one pipe and pumping the molten sulfur up through another pipe. Utah and Wyoming also produce some sulfur. In 1910 the domestic production was 255,000 long tons valued at \$4,605,000. At present only a small amount of sulfur is imported.

## B. MINERALS USED FOR THE EXTRACTION OF METALS AND ALLOYS

### 14. ALUMINUM

**Chief Mineral.** Bauxite.

**Producing Localities.** The United States leads in the production of bauxite. The states in order are Arkansas, Georgia, and Alabama.

**Treatment.** An electrolytic method is used. The mineral is first heated with sodium carbonate. Then carbon dioxide is introduced and forms aluminum hydroxid, which on heating gives aluminum oxid. The metal is obtained by the electrolysis of the oxid in a bath of cryolite which protects the metal from the air.

**Uses.** Aluminum has many uses; wire for transmission of electricity, cooking vessels, in various alloys such as aluminum bronze. A mixture of powdered aluminum and iron oxid with the trade name "thermit" is used for welding rails, crank shafts, etc., and for the extraction of such metals as tungsten, titanium, etc., from their ores.

**Production.** The domestic production of aluminum in 1910, 47,734,000 pounds valued at \$8,956,000.

## 15. ANTIMONY

**Chief Minerals.** Stibnite.

**Producing Localities.** France leads in the production of antimony. There are antimony deposits in Utah, Arkansas, Nevada and California, but the domestic production in 1910 was nil.

**Treatment.** The ore is fused with scrap iron and the impure metal called regulus is obtained which must be refined. In smelting, antimonial lead is produced and this is often made into type-metal directly.

**Uses.** Antimony is used principally in the manufacture of alloys such as type-metal, Babbitt metal, and Britannia metal.

**Production.** The domestic production of antimonial lead for 1910 was 14,000 short tons valued at \$1,338,000.

## 16. BISMUTH

**Chief Minerals.** Bismuth and bismuthinite.

**Producing Localities.** Bolivia stands first in the production of bismuth. The production in the United States is very slight. In former years Leadville, Colorado, furnished some bismuth.

**Uses.** Bismuth is used principally in the manufacture of easily fusible alloys.

## 17. COPPER

**Chief Minerals.** Copper, chalcocite, chalcopyrite, bornite, cuprite, malachite, azurite, and copper-bearing pyrite.

**Producing Localities.** The United States leads in the production of copper, its output being greater than the rest of the world combined. The three great copper producing states in order are Arizona, Montana, and Michigan, but Utah and California also produce notable amounts. In Arizona there are four important districts: Bisbee, Clifton-Morenci, Jerome, and Globe. The oxidized ores malachite, azurite, and cuprite were formerly the principal ores in Arizona, but now the sulfids are more important. In Montana the mines around Butte produce chalcocite, bornite, and enargite. In Michigan the ore is native copper disseminated through conglomerates and amygdaloids and runs less than 2 per cent. in copper.

**Treatment.** The native copper of Michigan is crushed and concentrated and the concentrates treated with limestone and slag in a reverberatory furnace.

The oxidized ores are smelted in the blast furnace with coke and the proper fluxes.

Sulfid ores are first roasted. Then on fusion in a reverberatory furnace a sulfid of copper and iron containing about 50 per cent. copper (called matte) is formed. The molten matte is treated in a converter in which fine streams of air drive off the sulfur and the result is blister copper, which contains about 98.5 per cent. of copper. Most of the copper except that from Michigan (called Lake copper) is refined electrolytically.

**Uses.** Copper is used principally in the electrical industry and in the manufacture of alloys such as brass, bronze, and German silver.

**Production.** In 1910 the domestic production was 1,080,159,000 pounds valued at \$137,180,000.



## 18. GOLD

**Chief Minerals.** Gold, calaverite, and sylvanite.

**Producing Localities.** The countries of the world in order of their production are Transvaal, United States, Australia, Russia, and Mexico. The states in order are Colorado, Alaska, California, Nevada, and South Dakota.

Gold is found mainly in two kinds of occurrences: in quartz veins with pyrite and other sulfids, and in placers along with other heavy minerals.

**Treatment.** Gold-bearing quartz is crushed in stamps and the gold caught on copper plated with mercury. The amalgam formed is removed at intervals and retorted. The residues were formerly treated with chlorin formed by the action of manganese dioxide and sulfuric acid on salt which dissolved the gold as chlorid.

The chlorination process is now replaced by the cyanide process by means of which very low grade ores may be treated. A weak solution of potassium cyanid percolates through the finely divided ore and dissolves the gold, which is later precipitated by zinc shavings.

Placer gold found in superficial deposits of sand, gravel, and conglomerate, which are derived by the breaking down of pre-existing rocks with quartz veins, are worked by hydraulic mining, by dredging, by drifting, or by surface placers. The gold is collected by amalgamation.

Gold is also obtained from base bullion derived from mixed ores, and in the electrolytic refining of copper.

**Production.** In 1910 the domestic production was 4,657,000 troy ounces valued at \$96,269,000 (coining value). The world's production for 1908 was \$443,400,000.

## 19. IRON

**Chief Minerals.** Hematite, limonite, and magnetite.

**Producing Localities.** The United States leads in the production of pig iron, while Germany is second and Great Britain third.

The most important locality in this country is the Lake Superior district comprising the Mesabi, Vermilion, and Cuyuna ranges of Minnesota, the Menominee and Gogebic ranges of Michigan and Wisconsin, and the Marquette and Crystal Falls range of Michigan. Of these the Mesabi range is the most important producer. About a hundred mines in the Lake Superior district each produce annually 100,000 tons or over of iron ore. Of states, Minnesota is in the lead, producing just about as much as all of the rest of the United States combined. The Hull Rust Mine at Hibbing, Minn., produced 3,190,000 long tons of iron ore in the year 1910. In the Lake Superior region hematite is the important ore mineral.

The next most important district is that of central Alabama, hematite being the important ore. This district owes its importance to the convenient location of iron ore, coal, and limestone.

In the Adirondack region of New York magnetite is mined.

In Virginia limonite is the principal iron ore. It occurs in residual clays overlying limestones.

Pennsylvania, New Jersey, Georgia, and Missouri also produce iron ores. In the western states, especially in Utah, are important ore-deposits which will be developed at some future time. But at present the high-grade ores (50 to 60 per cent. iron) of the Lake Superior region overshadow all others.

**Treatment.** The Lake Superior ores are shipped by Lake steamers to the blast furnaces of Pennsylvania and Ohio centering around Pittsburg. The ore is smelted in a blast furnace with coke and limestone by which pig-iron is produced. Pig-iron remelted and poured into molds is cast iron which contains about 5 per cent. of carbon and other impurities. Wrought iron is made by stirring molten cast iron in a puddling furnace lined with pure ferric oxid. The carbon of the pig-iron unites with the lining and leaves a very pure iron. Steel is now made in part directly from cast iron in a vessel called a converter. Blasts of air are passed through the molten iron, all the carbon

being converted into gases. Then weighed quantities of iron or alloys of iron containing known amounts of carbon are added. Steel contains 1 to 2 per cent. of carbon in the form of certain carbids which are necessary to give it hardness and other desirable properties. The open-hearth process is also used in the manufacture of steel.

**Production.** The domestic production of pig-iron for 1910 was 27,303,000 long tons valued at \$425,115,000.

## 20. METALS USED AS ALLOYS WITH STEEL

The following metals, chromium, manganese, molybdenum, nickel, titanium, tungsten, and vanadium, are alloyed with steel to increase its hardness, strength, toughness, tenacity, etc.

**Chromium.** Chromite is used. The principal sources of chromite are Asiatic Turkey and New Caledonia. California has important deposits, but the production is slight.

**Manganese.** Pyrolusite, psilomelane, and franklinite are the chief minerals. In the Lake Superior district manganiferous iron ores and in New Jersey the residue from the manufacture of zinc oxid are used in the steel industry. Manganese deposits are also worked in Virginia, Georgia, Arkansas, and California, but in 1908 the imports amounted to over a million dollars.

**Molybdenum.** Molybdenite is mined in this country principally at Crown Point, Washington, but the production is very small.

**Nickel.** Nickel-bearing pyrrhotite and garnierite are the chief sources of nickel, which is used in the manufacture of rails and armor plate. Nickel is obtained principally from the pyrrhotite of Sudbury, Canada, and from the garnierite of New Caledonia.

**Titanium.** Rutile is practically the only source of titanium. The only important domestic source of titanium is Nelson Co., Virginia.

**Vanadium.** Carnotite, a mixture of vanadium and uranium compounds; roscoelite, a vanadium mica; and patronite, a newly

discovered vanadium sulfid, all furnish vanadium. Carnotite and roscoelite occur disseminated in sandstone in western Colorado, while patronite is found only in Peru.

**Tungsten.** The most important tungsten mineral is wolframite, but hübnerite and scheelite have also been mined. Boulder County, Colorado, contains the largest deposits in this country. Tungsten is used extensively in the manufacture of tool-steel. In 1910 the domestic production of tungsten ores was 1800 short tons valued at \$807,000.

**Treatment.** There are two methods for the production of these metals and their ferro-alloys, the electric furnace and the Goldschmidt process. In the electric furnace the ferro-alloys are obtained directly from their ores by reduction. In the Goldschmidt process the metals or their ferro-alloys are made by igniting a mixture of powdered aluminum and oxid of the metal. The metal and the aluminum change places, aluminum oxid and the metal being formed.

## 21. LEAD

**Chief Mineral.** Galena.

**Producing Localities.** In the production of lead the United States ranks first, the principal states in order being Missouri, Idaho, Utah, and Colorado.

**Treatment.** The ore is heated in a blast furnace with coke and limestone, and base bullion, an impure lead often containing silver and gold, is the result. The silver is recovered by the process known as desilverization, metallic zinc being added to the molten lead. At a certain temperature an alloy of zinc and silver is formed as a scum on the surface and is removed.

**Uses.** Lead is used principally in the manufacture of white lead, lead piping and sheeting, and alloys such as type-metal and shot.

**Production.** In 1910 the domestic production was 372,000 short tons valued at \$32,756,000.

## 22. MERCURY

**Chief Mineral.** Cinnabar.

**Producing Localities.** Spain leads in the production of mercury, with Italy second, and the United States third. In this country California furnishes the bulk of the supply, though Texas is also an important producer. The New Almaden mine in Santa Clara County, California, has in the past been the greatest producer, but at present the New Idria mine in San Benito County, California, is the main source. These localities are named from famous quicksilver mines in Europe, Almaden in Spain and Idria in Austria.

**Treatment.** The ore is heated in retorts or at the large mines in furnaces resembling lime kilns. The mercury vaporizes readily and is condensed under water.

**Uses.** Mercury is used principally in the manufacture of vermilion and in the amalgamation of gold ores.

**Production.** In 1910 the domestic production was 20,000 flasks (75 pounds each) valued at \$958,000.

## 23. PLATINUM

**Chief Mineral.** Platinum.

**Producing Localities.** Russia is practically the only producer of platinum, the mineral occurring in placer deposits in the Ural Mts. Small amounts are recovered in northern California and southern Oregon from the gold placers. Colombia, South America, also furnishes some platinum.

**Treatment.** The concentrates are treated with dilute aqua regia which dissolves out most of the impurities. After dissolving in concentrated aqua regia the platinum is precipitated with ammonium chlorid as  $(\text{NH}_4)_2\text{PtCl}_6$ , which on heating leaves platinum containing a little iridium.

**Production.** In 1910 the domestic production was 773 troy ounces valued at \$25,277.

## 24. SILVER

**Chief Minerals.** Silver, argentite, pyrargyrite, proustite, stephanite, cerargyrite, and argentiferous galena.

**Producing Localities.** Mexico leads in the production of silver, with the United States second, and Canada third. In the United States the five leading states in order of production are Montana, Colorado, Nevada, Utah, and Idaho. Canada owes its rank as third place to the comparatively new discoveries at Cobalt.

**Treatment.** Most of the silver is obtained from argentiferous galena by the Parke's process. Zinc is added to molten lead and forms a zinc-silver alloy which has a lower melting point than lead. This alloy is skimmed off the molten lead and the zinc is distilled off. The silver is purified by cupellation.

Silver, together with gold, is obtained in the electrolytic refining of copper.

If the ore does not contain lead or copper the process known as pan amalgamation is used. The essential parts of the process are the reduction of silver by metallic iron, usually the bottom of the vessel, and subsequent amalgamation with mercury.

**Production.** In 1910 the domestic production of silver was 57,137,000 troy ounces valued at \$30,854,000.

## 25. TIN

**Chief Mineral.** Cassiterite.

**Producing Localities.** The Federated Malay States leads in the production of tin, followed by Bolivia and Australia. Cornwall, England, was formerly the principal producer. In the United States a little tin has been produced by Alaska, South Dakota, and South Carolina, but the amount has been very small.

**Treatment.** Tin ore is smelted in a reverberatory furnace with coal. The impure metal obtained is purified by reheating and by continued oxidation.

**Uses.** Tin is used in the production of tin-plate (sheet-iron coated with tin) and various alloys such as bronze.

**Production.** In 1910, 59 short tons of cassiterate ~~tin~~ were produced in the United States. The value of the imports, however, amounted to \$33,913,000 in 1910.

## 26. ZINC

**Chief Minerals.** Sphalerite, smithsonite, and calamine.

**Producing Localities.** Germany leads in the production of zinc, with the United States second and Belgium third. Of the states Missouri, Colorado, and Wisconsin are the main producers. The Joplin district in southwestern Missouri furnishes about 65 per cent. of the zinc produced in the United States.

**Treatment.** After crushing and concentrating, the zinc ore is roasted. It is then mixed with powdered coke and heated in clay retorts. The zinc volatilizes and forms in condensers attached to the retorts. This crude zinc is called spelter.

The ore from the Joplin district is shipped to Kansas principally, where natural gas furnishes a convenient fuel for smelting. In Colorado the smelters formerly deducted for zinc in ore, but now Colorado is an important producer. In New Jersey the zinc ores are used for the production of zinc white and very little for spelter.

**Uses.** Zinc is used principally in galvanizing iron and in the manufacture of brass, an alloy of copper and zinc.

**Production.** In 1910 the domestic production of spelter was 252,000 short tons valued at \$27,268,000.

## C. MINERALS USED IN THE CHEMICAL INDUSTRIES

### 27. ALUMINUM COMPOUNDS

The compounds manufactured are alum, aluminum sulfate, and the oxid, which is called alundum.

**Chief Mineral.** Bauxite, cryolite, and alunite.

**Producing Localities.** Bauxite is obtained in Georgia, Alabama, and Arkansas, cryolite in Greenland, and alunite in Italy.

**Treatment.** Alum is made from bauxite, cryolite, and alunite; aluminum sulfate from bauxite; and alundum from bauxite by heating in the electric furnace.

**Uses.** Alum is used principally in the manufacture of paper, aluminum sulfate in dyeing (as a mordant to fix the color), and alundum as an abrasive.

**Production.** In 1910 the domestic production of alum and aluminum sulfate was 105,000 short tons valued at \$2,000,000, and of alundum, 13,410,000 pounds valued at \$804,600.

## 28. ARSENIOUS OXID

**Chief Mineral.** Arsenopyrite.

**Producing Localities.** Cornwall formerly furnished the principal supply, but now Germany leads with France second. In this country arsenious oxid is produced at Everett, Washington, and from the smelter fumes at Anaconda, Montana.

**Treatment.** Arsenopyrite on roasting gives off arsenious oxid,  $As_2O_3$ . At the Washoe smelter, Anaconda, Montana, the enargite of the ore furnishes the arsenious oxid.

**Uses.** The principal use of arsenious oxid is in the manufacture of paris green and london purple, valuable insecticides, but there are many minor uses.

**Production.** In 1910 the domestic production was 2,994,000 pounds valued at \$52,000.

## 29. BORAX AND BORACIC ACID

**Chief Minerals.** Colemanite.

**Producing Localities.** San Bernardino, Ventura, and Inyo counties, California, furnish all the colemanite produced.

**Treatment.** Borax is made from colemanite by decomposing it with sodium carbonate. Boracic acid is obtained from colemanite by the use of sulfuric acid. Most of the California borax is refined at Bayonne, New Jersey.



**Uses.** Borax and boracic acid are used in the manufacture of soap, glass, toilet preparations, food preservatives, etc.

**Production.** The domestic production of crude borax in 1910 was 42,300 short tons valued at \$1,202,000.

### 30. BROMIN

Bromin is obtained from the bittern or salt brines of Michigan, Ohio, and West Virginia, as a by-product in the salt industry.

Bromin is used principally in photography and in medicine.

The domestic production in 1910 was 245,000 pounds valued at \$41,000.

### 31. COBALT COMPOUNDS

Smalt, a cobalt silicate, is about the only compound used to any great extent.

**Chief Minerals.** Smaltite and asbolite (cobaltiferous wad).

**Producing Localities.** New Caledonia and Cobalt, Ontario, furnish the principal supply of cobalt.

**Uses.** Smalt is used as a pigment, especially for glass and pottery.

### 32. CHROMIUM COMPOUNDS

Potassium and lead chromates, chrome alum, and chromium oxid.

**Chief Mineral.** Chromite.

**Producing Localities.** New Caledonia and Asia Minor furnish the bulk of the supply.

**Uses.** The chromium compounds mentioned are used in dyeing, in tanning, and in the manufacture of paints.

**Production.** The domestic production of chromite in 1910 was 205 long tons valued at \$2,700.

### 33. IODIN

Iodin is obtained principally from the impure sodium nitrate of Chile, where it occurs as a calcium iodate.

### 34. LITHIUM SALTS

**Chief Minerals.** Lepidolite, spodumene, and amblygonite.

**Producing Localities.** Pala, San Diego Co., California, and the Black Hills, South Dakota, have furnished the domestic supply.

**Uses.** Lithium carbonate is used for medicinal purposes, especially in artificial mineral waters.

**Production.** In 1908 the domestic production of lithium minerals was 203 short tons valued at \$1550.

### 35. MAGNESIUM COMPOUNDS

Magnesia ( $MgO$ ) and epsom salts ( $MgSO_4 \cdot 7H_2O$ ) are the compounds used.

**Chief Mineral.** Magnesite.

**Producing Localities.** Austria and Greece furnish the principal supply of magnesite. In California there are several important deposits, Porterville and Red Mt. near Livermore being the principal ones.

**Treatment.** Magnesite on heating gives off carbon dioxide, which is liquefied for use in soda fountains, and leaves magnesite. Epsom salts is made by dissolving magnesite in sulfuric acid.

**Uses.** Magnesia is used in the manufacture of refractory bricks, paper, boiler coverings, etc.

**Production.** In 1910 the domestic production was 12,400 short tons valued at \$74,000.

### 36. NITRATES

**Chief Mineral.** Soda Niter.

**Producing Localities.** Chili furnishes the total supply. Although the exports from Chili amount to about a million tons a year it is said that the deposits will last 200 or 300 years at the present rate of exportation. A little soda niter is found in the desert regions of California.

**Uses.** Soda niter is used as a fertilizer, and in making potassium nitrate.

### 37. POTASSIUM SALTS

Potassium chlorid, nitrate, and sulfate.

**Chief Minerals.** Carnallite and kainite.

**Producing Localities.** Germany produces practically the entire supply of potassium salts. Potassium chlorid and sulfate are obtained from carnallite and kainite by solution and recrystallization. The nitrate is made by crystallizing a water solution of potassium chlorid and sodium nitrate.

**Uses.** Potassium chloride and sulfate are used as fertilizers, potassium nitrate principally in the manufacture of gunpowder.

### 38. SODIUM SALTS

**Chief Mineral.** Halite or rock-salt.

**Producing Localities.** Austria-Hungary leads in the production of salt, followed by the United States and Germany. In this country the states in order of production are Michigan, New York, Kansas, and Ohio.

**Treatment.** Salt occurs in thick bedded deposits often associated with gypsum or anhydrite. The salt is sometimes mined in the form of rock-salt just as coal would be mined. At other localities water is forced down and the resulting brine is evaporated. In some places sea or lake water is evaporated to obtain salt.

Soda or sodium carbonate, next to sodium chlorid, is the principal sodium salt used. The Solvay process for the manufacture of soda is as follows: ammonia gas and carbon dioxide are passed into a solution of salt. Sodium bicarbonate is formed, which on heating gives normal sodium carbonate.

Caustic soda is made from soda and calcium hydroxid.

**Uses.** Salt is used in the packing-house industry, soda is used in manufacture of glass, and caustic soda in the manufacture of soap.

**Production.** In 1910 the domestic production was 30,000,000 barrels (280 lbs. net) valued at \$7,900,000.

### 39. STRONTIUM COMPOUNDS

**Chief Minerals.** Strontianite and celestite.

**Producing Localities.** Germany is practically the only producer.

**Uses.** Strontium hydroxid is used in the refining of beet-sugar and strontium nitrate in pyrotechnics.

### 40. SULFURIC ACID

**Chief Mineral.** Pyrite.

**Producing Localities.** Portugal leads in the production of pyrite, with the United States second. In this country about half of the pyrite is produced in Virginia.

**Treatment.** The ore is roasted in specially designed furnaces. The sulfur dioxid is forced into lead chambers where steam and nitrogen dioxid convert it into sulfuric acid.

**Uses.** Sulfuric acid is the basis of many industries. In order of the amount of acid used, these industries are superphosphate for fertilizer, refining of petroleum, pickling iron and steel, ammonium sulfate, alum and aluminum sulfate, manufacture of other acids, blue vitriol, etc.

**Production.** In 1910 the domestic production of pyrite was 238,000 long tons valued at \$958,000. For 1908 the imports amounted to \$2,264,000.

### 41. THORIA

**Chief Mineral.** Monazite.

**Producing Localities.** The principal localities are North and South Carolina and Bahia, Brazil.

**Treatment.** The monazite which occurs in the form of sand is decomposed by sulfuric acid. The addition of oxalic acid converts sulfates into oxalates. Ammonium oxalate dissolves out the thorium oxalate, which is converted into thoria by heating.

**Uses.** Thoria is used in making Welsbach gas mantles.

**Production.** The domestic production of monazite and zircon in 1910 was 99,300 pounds valued at \$12,000.

## **42. ZINC OXID**

**Chief Minerals.** Franklinite, willemite, and zincite.

**Producing Locality.** Sussex Co., New Jersey, furnishes the only supply of these minerals.

**Treatment.** Zinc oxid is made directly from the ores by heating in a special type of furnace. The residues, which contain a large percentage of manganese, are made into spiegeleisen and ferromanganese, used in steel making.

**Uses.** Zinc oxid is a valuable paint which does not tarnish like white lead.

**Production.** In 1910 the domestic production was 59,000 short tons valued at \$5,325,000.

## GLOSSARY

- Absorption.** A term referring to the intensity of light in different directions in a crystal.
- Achroite.** A colorless variety of tourmaline.
- Acicular.** Needle-shaped.
- Acid salt.** A compound in which only part of the hydrogen of an acid is replaced by a metal.
- Acute bisectrix.** The line bisecting the axial angle.
- Adamantine.** Brilliant luster like that of cerussite.
- Adularia.** A glassy variety of orthoclase found in veins.
- Agalite.** Fibrous talc pseudomorphous after enstatite.
- Agate.** A variegated chalcedony.
- Alabaster.** Translucent massive gypsum.
- Aggregate polarization.** The extinction of a mass of particles or fibers at different times.
- Aggregate structure.** The structure which causes aggregate polarization.
- Alexandrite.** A variety of chrysoberyl.
- Almandite.** A sub-species of garnet containing Fe and Al.
- Alpha ( $\alpha$ ).** (1) The angle between the *b* and *c* axes. (2) The shortest indicatrix axis.
- Alteration.** A change in chemical composition due to circulating waters, weathering, etc.
- Aluminates.** Salts of  $H_2AlO_3$ ,  $HAIO_2$ , etc.
- Aluminum minerals.** Alunite, amblygonite, andalusite, bauxite, corundum, cryolite, cyanite, diasporé, sillimanite, spinel, topaz, turquois, wavelite, and many silicates.
- Alundum.** Artificial corundum used as an abrasive.
- Alum-stone.** An impure siliceous alunite.
- Amazon-stone.** A green variety of microcline.
- Amethyst.** A purple variety of quartz.
- Amethyst, oriental.** A purple variety of corundum.
- Ammonium minerals.** Sal-ammoniac.
- Amorphous.** Totally devoid of crystalline form or structure.
- Amphibole.** A group of silicates including tremolite, actinolite, hornblende, and glaucophane.
- Amygdaloidal.** Referring to amygdules.

- Amygdules.** Secondary minerals filling rounded cavities in volcanic rocks.
- Analyzer.** The upper nicol.
- Andesine.** A plagioclase between oligoclase and labradorite.
- Andesite.** A volcanic rock composed essentially of plagioclase and hornblende.
- Andradite.** A sub-species of garnet containing Ca and Fe<sup>++</sup>.
- Angle, axial.** The angle between the optic axes.
- Angle, interfacial.** The dihedral angle between two faces.
- Anhedral.** Without crystal faces.
- Anisotropic.** Substances with double refraction.
- Antimonates.** Salts of  $H_3SbO_4$ ,  $HSbO_3$ , etc.
- Antimonites.** Salts of  $H_3SbO_3$ ,  $HSbO_2$ , etc.
- Antimony minerals.** Antimony, bournonite, jamesonite, polybasite, pyrrhgyrite, stephanite, stibiconite, stibnite, tetrahedrite.
- Antimony glance.** Synonym of stibnite.
- Antimony ocher.** Synonym of stibiconite.
- Aquamarine.** A pale sea-green variety of beryl.
- Arborescent.** Branching like a tree.
- Arkose.** A feldspathic sandstone.
- Arsenates.** Salts of  $H_3AsO_4$ ,  $HAsO_3$ , etc.
- Arsenites.** Salts of  $H_3AsO_3$ ,  $HAsO_2$ , etc.
- Arsenic minerals.** Arsenic, arsenopyrite, cobaltite, enargite, löllingite, mimetite, niccolite, olivenite, orpiment, proustite, realgar, smaltite.
- Arsenical pyrites.** A synonym of arsenopyrite.
- Asbestos.** Fibrous tremolite or fibrous serpentine.
- Asterism.** A six-rayed star effect seen by holding certain minerals up to the light.
- Astringent.** A taste that puckers the lips.
- Asymmetric class.** The class without any symmetry.
- Asymmetric dispersion.** The dispersion which produces an interference figure without any symmetry of color distribution.
- Axes of reference.** Coördinate axes to which crystal faces are referred.
- Axes of symmetry.** Lines about which a crystal may be revolved so that it occupies the same position in space.
- Axial angle.** The angle between the optic axes.
- Axial cross.** Coördinate axes or axes of reference.
- Axial elements.** The axial ratio and the angles between the axes.
- Axial plane.** The plane of the optic axes.
- Axial ratio.** The relative lengths on the axes cut off by the unit face.
- Barium minerals.** Barite, witherite.
- Barytes.** Synonym of barite.
- Basal pinacoid.** The pinacoid {001} or {0001}.

- Basalt.** A dense volcanic rock composed chiefly of plagioclase and augite with a glassy groundness.
- Basaltic hornblende.** A variety of hornblende found in volcanic rocks.
- Basanite.** A black compact variety of chalcedony.
- Basic rocks.** Igneous rocks comparatively low in silica ( $\text{SiO}_2 < 50\%$ ).
- Basic salts.** Compounds in which only part of the hydroxyl of a base is replaced by an acid radical.
- Bastite.** A pseudomorph of serpentine after bronzite.
- Batholith.** A deep-seated mass of igneous rock of indeterminate shape.
- Baveno twin.** An orthoclase twin with {021} as twin plane.
- Becke test.** A test for relative indices of refraction.
- Berlin blue.** An anomalous interference color of the first order.
- Bertrand lens.** A small lens inserted in the microscope tube to magnify the interference figure.
- Beryllium minerals.** Beryl and chrysoberyl.
- Beta ( $\beta$ ).** (1) The angle between the  $a$ - and  $c$ -axes. (2) The indicatrix axis normal to the plane of  $\alpha$  and  $\gamma$ .
- Biaxial.** An optical term for crystals of the orthorhombic, monoclinic, and triclinic systems.
- Bipyramid.** A double-ended pyramid.
- Birefringence.** The strength of the double refraction denoted by  $(\gamma - \alpha)$ .
- Bisectrix.** The line bisecting the angle between the optic axes.
- Bisilicates.** The same as metasilicates,  $\text{R}''\text{SiO}_3 = \text{R}'\text{O} \cdot \text{SiO}_2$ .
- Bismuth flux.** A mixture of 2 parts S, 1 part KI, and 1 part  $\text{KHSO}_4$ .
- Bismuth minerals.** Bismuth, bismuthinite.
- Bisphenoid.** A form apparently consisting of two sphenoids placed together symmetrically.
- Blackband.** An impure carbonaceous siderite.
- Black jack.** A synonym of ferriferous sphalerite.
- Blende.** A synonym of sphalerite.
- Blue-john.** A banded fluorite used for ornamental purposes.
- Bog iron ore.** A synonym of limonite.
- Bog manganese.** A synonym of wad.
- Bone-ash.** Calcium phosphate used in silver cupellation.
- Borates.** Salts of  $\text{H}_3\text{BO}_3$ ,  $\text{HBO}_2$ ,  $\text{H}_2\text{B}_4\text{O}_7$ , etc.
- Boracic acid flux.** A mixture of 1 part fluorite and 4 parts  $\text{KHSO}_4$ .
- Boron minerals.** Axinite, boracite, borax, colemanite, datolite, ulexite.
- Bort.** A variety of diamond without distinct form or cleavage.
- Botryoidal.** Resembling a bunch of grapes.
- Brachy-axis.** The  $a$ -axis in the orthorhombic and triclinic systems.
- Brachy-dome.** The form {0 $kl$ } in the orthorhombic and triclinic systems.
- Brachy-pinacoid.** The form {010} in the orthorhombic and triclinic systems.
- Breccia.** A rock made up of coarse angular fragments cemented together.



- Brittle mica.** Synonym of margarite.
- Brittle silver ore.** Synonym of stephanite.
- Bronze mica.** Synonym of phlogopite.
- Bytownite.** A basic plagioclase between labradorite and anorthite.
- Calcareous tufa.** A porous calcium carbonate formed by springs.
- Calc-spar.** A synonym of calcite.
- Calcium minerals.** Anhydrite, ankerite, apatite, aragonite, calcite, colemanite, dolomite, fluorite, gypsum, scheelite, wollastonite and many silicates.
- Campylite.** A mineral intermediate between pyromorphite and mimetite.
- Capillary.** Hair-like.
- Carbon minerals.** Graphite, diamond, and carbonates.
- Carbonado.** A black opaque variety of diamond.
- Carbonates.** Salts of  $H_2CO_3$ .
- Carborundum.** An artificial silicon carbide.
- Carlsbad twin.** A penetration twin of the feldspars with *c* as the twin-axis.
- Carnotite.** A potassium uranium vanadium compound. It is probably a mixture.
- Center of symmetry.** A crystal that has for every face a similar opposite parallel face has a center of symmetry.
- Cerium minerals.** Allanite, monazite.
- Chalcotrichite.** A capillary variety of cuprite.
- Chalk.** A fine-grained calcium carbonate rock formed by organisms.
- Chatoyant.** With an opalescent reflection or radiation.
- Chalybite.** A synonym of siderite.
- Chert.** A massive chalcedony rock.
- Chessylite.** A synonym of azurite.
- Chiastolite.** A variety of andalusite with regularly arranged carbonaceous material.
- Chlorids.** Salts of HCl.
- Chlorin minerals.** Atacamite, boracite, apatite, carnallite, cerargyrite, halite, mimetite, pyromorphite, sal-ammoniac, sylvite, sodalite, vanadinite, wernerite.
- Chlorite.** A group of silicates.
- Chondrules.** Rounded nodules occurring in meteorites.
- Chromates.** Salts of  $H_2CrO_4$ .
- Chrome garnet.** Synonym of uvarovite.
- Chrome iron ore.** Synonym of chromite.
- Chromites.** Salts of  $H_2CrO_3$ ,  $HCrO_2$ , etc.
- Chromium minerals.** Chromite, crocoite, and uvarovite.
- Chrysolite.** A synonym of olivine.
- Chrysotile.** A fibrous variety of serpentine.

- Chrysoprase.** An apple-green, chalcedony.
- Clastic.** Made up of fragments of preëxisting rocks.
- Clay.** A mixture of hydrous aluminum silicates with feldspar, quartz, etc.
- Cleavage.** The property of breaking in certain crystallographic directions.
- Closed form.** A crystal form that encloses space of itself.
- Clino-axis.** The  $a$ -axis in the monoclinic system.
- Clinopinacoid.** The form  $\{010\}$  in the monoclinic system.
- Clinodome.** The form  $\{0kl\}$  in the monoclinic system.
- Cobalt minerals.** Cobaltite, erythrite, smaltite.
- Color chart.** The interference colors of a wedge placed on a diagram.
- Colors, interference.** The colors of doubly refracting substances as seen in polarized light.
- Combination.** A crystal composed of two or more forms.
- Columnar.** Made up of coarse, more or less parallel, aggregates.
- Complementary forms.** Two forms which combined geometrically produce a form with higher symmetry.
- Composite symmetry.** The recurrence of similar faces by rotation about an axis combined with reflection in a plane normal to the axis.
- Composition face.** The face of union of the parts of a twin crystal.
- Conchoidal fracture.** Curved fracture like the surface of a shell.
- Concretion.** Nodular masses often fantastic in shape.
- Conglomerate.** A rock made up of coarse, rounded fragments cemented together.
- Congruent forms.** Two forms which may each be derived from the other by rotation.
- Conoscope.** A polariscope for convergent light.
- Contact goniometer.** A cardboard or metal protractor for measuring angles.
- Contact metamorphism.** Metamorphism produced by the heat of an igneous intrusion.
- Contact minerals.** Minerals formed by contact metamorphism.
- Contact twin.** A twin with definite composition face.
- Copper minerals.** Atacamite, azurite, bornite, bournonite, brochantite, chalcantite, chalcocite, chalcopyrite, chrysocolla, copper, covellite, cuprite, enargite, malachite, melaconite, olivenite, stannite, tetrahedrite
- Copperas.** Synonym of  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ .
- Copper glance.** Synonym of chalcocite.
- Copper pyrites.** Synonym of chalcopyrite.
- Cordierite.** Synonym of iolite.
- Crossed nicols.** Two Nicol prisms with their vibration planes at right angles.
- Crossed dispersion.** The dispersion which produces an interference figure with color distribution symmetrical to the center of the figure.
- Crystal class.** The sum of all crystals with the same symmetry.
- Crystalline limestone.** A metamorphic limestone.

**Crystallites.** Minute hair or fern-like forms which are supposed to be incipient crystals.

**Cube.** A parallelepiped composed of six similar faces at right angles to each other.

**Cupellation.** The removal of lead from lead-silver alloy by volatilization and absorption by bone-ash.

**Cyclic twin.** A repeated twin which tends to form a circle.

**Dacite.** A volcanic rock intermediate between rhyolite and andesite.

**Decrepitate.** Flies to pieces when heated.

**Deltahedron.** An isometric form of 12 faces with the symbol  $\{hhl\}$ .

**Deliquescent.** Absorbing water from the air.

**Dendritic.** Branching like a tree.

**Diabase.** An igneous rock composed essentially of plagioclase and augite with ophitic texture.

**Diallage.** A lamellar variety of diopside.

**Dichroic.** A substance with two axial colors.

**Dichroscope.** An instrument for observing pleochroism.

**Dike.** A tabular mass of intrusive igneous rock.

**Diploid.** The general form of the diploidal class.

**Diploidal class.** The class with the symmetry  $3A_2.3P.4A_2$ .

**Dimorphism.** The occurrence of a substance in two modifications which differ in crystallization.

**Diorite.** A plutonic igneous rock composed essentially of plagioclase and hornblende.

**Dispersion.** The divergence of the optical constants for different parts of the spectrum.

**Dodecahedron.** The form  $\{110\}$  in the isometric system.

**Dodecants.** One of the twelve divisions into which space is divided by the four axes of the hexagonal system.

**Dog-tooth spar.** A variety of sharp-pointed calcite crystals.

**Dolomitization.** The process by which calcium carbonate is converted into dolomite.

**Dome.** A form consisting of two faces astride a plane of symmetry.

**Domatic class.** The crystal class with a plane of symmetry.

**Double refraction.** The property of splitting a ray of light into two rays.

**Drusy.** A surface apparently sprinkled with minute crystals.

**Dry-bone.** A local synonym of either smithsonite (Wis.) or cerussite (Mo.).

**Ductile.** Capable of being drawn into wire.

**Dunite.** An igneous rock composed almost entirely of olivine.

**Eclogite.** A metamorphic rock composed of pyroxene or amphibole with garnet.

- Edge.** The intersection of two crystal faces.
- Effervescence.** The bubbling caused by the evolution of such gases as  $\text{CO}_2$  and  $\text{H}_2\text{S}$ .
- Efflorescent.** Gives up its water of crystallization on standing.
- Elaeolite.** A synonym of nephelite.
- Elastic.** An elastic mineral springs back when bent.
- Electrum.** A natural alloy of gold and silver with over 20% of silver.
- Elements, axial.** The relative intercepts of the unit form and the angles between the axes.
- Elements of symmetry.** Axis, plane, and center of symmetry.
- Emerald.** The clear green variety of beryl.
- Emery.** A mixture of corundum with either magnetite or hematite.
- Empirical formula.** The simplest method of expressing the chemical composition without regard to structure or constitution.
- Enantiomorphous.** Two compounds are enantiomorphous when they are the mirror-image of each other.
- Endlichite.** An isomorphous mixture of mimetite and vanadinite.
- Erubescite.** A synonym of bornite.
- Essonite.** A variety of garnet.
- Etch-figures.** The small geometric figures produced on crystal faces by a solvent.
- Ether.** A hypothetical substance necessary to explain the transmission of light.
- Exfoliate.** To swell up or to spread out like the leaves of a book.
- Extinction.** The position of darkness of a doubly-refracting crystal between crossed-nicols.
- Extinction angle.** The angle between the extinction direction and the crystal outline.
- Extinction direction.** The position of extinction.
- Extraordinary ray.** In doubly refracting substances the ray which produces the image that revolves around the fixed image.
- Extrusive.** A term applied to igneous rocks which have been poured out on the surface.
- Face.** One of the flat, more or less smooth, surfaces of a crystal.
- Face color.** The color of a crystal when viewed in a particular direction.
- Facet.** The polished surface of a cut-stone.
- Fahlerz.** The German name for tetrahedrite.
- Felsite.** A volcanic igneous rock with fine granular texture and without phenocrysts.
- Felsitic.** A fine granular texture, applied to igneous rocks.
- Feldspathoid.** Leucite, nephelite, and sodalite are called feldspathoids because in igneous rocks they often take the place of the feldspars.

- Ferro-alloys.** Alloys of iron or steel with various elements.
- Ferro-magnesium.** The rock-forming minerals, augite, hornblende, olivine, biotite, etc., which contain Fe and Mg.
- Fibrous.** Made up of fibers.
- Fire-opal.** A variety of opal with red reflections.
- Flexible.** Capable of being bent and remaining so.
- Flint.** A variety of chalcedony.
- Fluorids.** Salts of HF.
- Fluorin minerals.** Apatite, amblygonite, chondrodite, cryolite, fluorite, lepidolite, topaz.
- Fluor spar.** Synonym of fluorite.
- Foliated.** Made up of flat plates.
- Fool's gold.** Synonym of pyrite.
- Form.** The sum of like faces on a crystal.
- Form, closed.** A form which encloses space of itself.
- Form, open.** A form which does not enclose space of itself.
- Formula weight.** The sum of the atomic weights of the elements.
- Fowlerite.** A zinc-bearing variety of rhodonite.
- Fracture.** The manner of breaking when not cleavable.
- Freibergite.** Argentiferous tetrahedrite.
- French chalk.** A kind of talc used by tailors.
- Friable.** Capable of being pulverized by rubbing between the fingers.
- Fusibility, scale of.** A list of minerals ranging from very easily fusible stibnite to infusible quartz.
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- Gabbro.** A basic plutonic rock composed of basic plagioclase and diorite.
- Galenite.** Synonym of galena.
- Gamma ( $\gamma$ ).** (1) The angle between the  $a$  and  $b$  axes. (2) The longest indicatrix axis.
- Gangue.** The non-metallic part of a vein.
- Gelatinization.** Solubility with the formation of jelly-like silica.
- General form.** The form  $\{hkl\}$  or  $\{hk\bar{l}\}$  in any crystal class.
- Geode.** A hollow concretion usually lined with crystals.
- Geyserite.** A variety of opal silica formed in hot spring deposits.
- Glance.** A general name for metallic sulfids.
- Glass, natural.** Volcanic rocks such as obsidian, pitchstone, pumice, etc.
- Gliding.** A molecular rearrangement due to twinning.
- Globular.** Made up of more or less complete spheres.
- Gnomonic projection.** A projection made on a plane tangent to a sphere.
- Gold minerals.** Calaverite, electrum, gold, sylvanite.
- Goniometer.** An instrument used for measuring the angles of crystals.
- Gossan.** The upper oxidized portion of a vein or ore deposit.

**Granite.** A plutonic igneous rock composed essentially of quartz and orthoclase.

**Granitic or granitoid.** The even-grained texture of a granite.

**Graphic granite.** An intergrowth of quartz and orthoclase.

**Graphic texture.** The texture of graphic granite.

**Graphitic acid.** A substance formed by the action of  $\text{KClO}_3$  and conc.  $\text{HNO}_3$  on graphite.

**Gravel.** A coarse fragmental deposit.

**Gray copper ore.** A synonym of tetrahedrite.

**Greisen.** A quartz-muscovite rock formed by pneumatolysis.

**Greenstone.** A dense metamorphic rock.

**Grossularite.** A sub-species of garnet containing Ca and Al.

**Guano.** A phosphatic deposit formed by the leaching of bird and bat excreta.

**Gypsum wedge.** A thin wedge-shaped slice of selenite.

**Gyroid.** The general form of the gyroïdal class.

**Gyroïdal class.** The crystal class with  $6A_2 \cdot 4A_3 \cdot 3A_4$ .

**Habit, crystal.** The general shape of a crystal as determined by growth in certain directions.

**Hackly.** A term applied to the fracture of metals.

**Haloids.** Salts of HCl, HBr, HI, and HF.

**Heavy liquids.** Liquids such as methylene iodid and potassium mercury iodid used for specific gravity determinations.

**Heavy spar.** Synonym of barite.

**Hematite, brown.** Synonym of limonite.

**Hemi-dome.** The form  $\{h0l\}$  in the monoclinic system is sometimes called a hemi-dome.

**Hemihedral.** The forms with lower symmetry than the holohedral.

**Hemimorphic.** Having two ends of the crystal differently terminated.

**Hemi-prism.** The form  $\{hk0\}$  in the triclinic system.

**Hemi-pyramid.** The form  $\{hkl\}$  in the monoclinic system.

**Hexagonal system.** The sum of all classes with a single 3-fold or 6-fold axis of symmetry.

**Hexahedron.** Synonym of a cube.

**Hexoctahedral class.** The class with the symmetry  $6A_2 \cdot 4A_3 \cdot 3A_4 \cdot 9P$ .

**Hexoctahedron.** An isometric form consisting of 48 faces.

**Hextetrahedral class.** The class with the symmetry  $3A_2 \cdot 4A_3 \cdot 6P$ .

**Hextetrahedron.** An isometric form with 24 faces.

**Hiddenite.** An emerald-green variety of spodumene.

**Holohedral.** A name sometimes applied to the class that has the highest symmetry in each system.

**Horizontal dispersion.** The dispersion which produces an interference figure

with color distribution symmetrical with respect to a line normal to the axial plane.

**Hornfels.** A dense rock formed by the contact metamorphism of shales.

**Horn silver.** Synonym of cerargyrite.

**Hyacinth.** A variety of zircon.

**Hyalite.** The glassy variety of opal.

**Hydrous salts.** Salts with so-called water of crystallization.

**Hydroxids.** Compounds of elements with hydroxyl.

**Hydroxyl.** The radical or ion (OH).

**Iceland spar.** Transparent calcite showing double refraction.

**Icosahedron.** One of the regular Platonic solids with twenty faces, an impossible crystallographic form.

**Icositetrahedron.** A synonym of the isometric trapezohedron.

**Ideal form.** A form in which like faces are of the same size and shape.

**Idocrase.** A synonym of vesuvianite.

**Igneous rocks.** Rocks formed by the consolidation of molten magma.

**Imitative forms.** The shapes of minerals which resemble other natural objects.

**Inclined dispersion.** The dispersion which produces an interference figure with color distribution symmetrical to the trace of the axial plane.

**Inclusions.** Foreign substances caught when crystals are being formed.

**Index of refraction.** A number which indicates the amount of bending of a ray of light on going from one medium into another.

**Indicatrix.** An ellipsoid, spheroid, or sphere used as an aid in studying crystal optics.

**Indices, Miller.** The reciprocal ratios of intercepts in terms of a selected unit.

**Indicolite.** A deep blue variety of tourmaline.

**Intercepts.** Distances cut off on axes of reference by planes.

**Interfacial angle.** The dihedral angle between two faces.

**Interference.** The result of two light waves travelling along the same path after one has been retarded.

**Interference colors.** The effects of interference as seen in white light.

**Interference figure.** The image produced by certain crystal plates when viewed in convergent polarized light.

**Intergrowth.** An intimate regular arrangement of two substances produced by simultaneous crystallization.

**Intrusive.** Igneous rocks which have invaded other rocks are called intrusive.

**Intumescence.** A bubbling up due to escape of water when heating a mineral.

**Inversion.** The operation indicated by an composite axis of two-fold symmetry.

**Iridescence.** A rainbow effect produced by interference of light in thin films.

**Iron minerals.** Ankerite, arsenopyrite, biotite, bornite, chalcopyrite, chromite, columbite, cupapite, franklinite, goethite, hematite, ilmenite, iron, limonite, löllingite, magnetite, marcasite, melanterite, olivine, pyrite, pyrrhotite, siderite, triphylite, vivianite, wolfamite, and some silicates

**Iron-pyrites.** A synonym of pyrite.

**Isodimorphism.** Two parallel isomorphous groups one or more of which in each group is dimorphous.

**Isomorphism.** The property of similar chemical compounds crystallizing in similar forms.

**Isomorphous mixtures.** A solid solution of two or more isomorphous substances.

**Isotropic.** Usually means optically isotropic. This term is synonymous with singly refracting.

**Jade.** A compact tough green or greenish-white ornamental stone composed of either an amphibole or pyroxene mineral.

**Jargon.** A pale-colored variety of zircon.

**Jasper.** A red, yellow, or brown variety of chalcedony colored by iron oxids.

**Jolly balance.** A specific gravity balance made of a spiral brass wire.

**Kaolin.** A mixture of kaolinite with other aluminous silicates.

**Kaolinization.** The process by which the feldspars are converted into kaolin.

**Kidney-ore.** A variety of hematite.

**Kunzite.** A variety of spodumene used as a gem.

**Kyanite.** The same as cyanite.

**Laccolite.** A dome-shaped mass of igneous rock, the intrusion of which arches the overlying strata.

**Lamellar.** Made up of plates.

**Laminæ.** Thin layers.

**Lapilli.** Small fragments of volcanic rocks produced by the explosive action of volcanoes.

**Lead minerals.** Anglesite, bournonite, cerussite, crocoite, galena, jamesonite, mimetite, pyromorphite, vanadinite, wulfenite.

**Lenticular.** Lens-shaped.

**Light, polarized.** Light in which the vibrations are in one plane.



**Limestone.** A sedimentary rock consisting of  $\text{CaCO}_3$ .

**Limestone, crystalline.** A metamorphic rock derived from a sedimentary limestone.

**Limit form.** Any form except  $\{hkl\}$  and  $\{hk\bar{l}\}$ .

**Lithium minerals.** Amblygonite, lepidolite, spodumene, triphylite.

**Lodestone.** A variety of magnetite which is a magnet itself.

**Luster.** A term applied to the quality of light reflected from a surface.

**Macle.** Synonym of a twin-crystal.

**Macro-axis.** The  $b$ -axis (long) in orthorhombic and triclinic crystals.

**Macrodome.** The form  $\{h0l\}$  parallel to the macro- or  $b$ -axis in the orthorhombic and triclinic systems.

**Macropinacoid.** The pinacoid  $\{100\}$  in the orthorhombic and triclinic systems.

**Macroscopic.** The same as megascopic.

**Magma.** The liquid mass from which igneous rocks originate by cooling and solidification.

**Magnesium minerals.** Actinolite, ankerite, boracite, brucite, carnallite, chondrodite, dolomite, enstatite, epsomite, hydromagnesite, hypersthene, kainite, magnesite, olivine, sepiolite, serpentine, spinel, talc, tremolite and other silicates.

**Magnetic pyrites.** Synonym of pyrrhotite.

**Magnetic iron ore.** Synonym of magnetite.

**Malleable.** Capable of being hammered out flat.

**Mammillary.** A surface consisting of rounded protuberances.

**Manebach.** One of the twinning laws of orthoclase.

**Manganese minerals.** Alabandite, franklinite, hübnerite, manganite, psilomelane, pyrolusite, rhodochrosite, rhodonite, wad.

**Marble.** Any limestone capable of taking a good polish.

**Martite.** A hematite pseudomorph after magnetite.

**Massive.** Without definite form or shape.

**Meerschaum.** Synonym of sepiolite.

**Megascopic.** Can be seen with the naked eye.

**Melanite.** A variety of andradite garnet.

**Menaccanite.** Synonym of ilmenite.

**Mercury minerals.** Cinnabar, mercury.

**Metals.** Elements which replace the hydrogen of acids.

**Metalloids.** Semi-metals such as As, Sb, and Bi.

**Metasilicates.** Salts of  $\text{H}_2\text{SiO}_3$ .

**Metasomatic replacement.** The replacement of a rock mass or vein, in which the original structure is retained.

**Metasomatism.** The same as metasomatic replacement.

**Meteorites.** Celestial bodies composed of iron and various silicates which occasionally enter the earth's atmosphere.

- Methylene iodid.** A heavy liquid used in specific gravity determinations.
- Micas.** A group of silicate minerals.
- Micaceous.** Made up of readily separable plates.
- Microchemical tests.** Chemical tests made on a small scale. The form, color, and optical properties of the minute crystals produced are used.
- Microcosmic salt.** The same as salt of phosphorus.
- Microlites.** Minute crystals found in obsidians and related rocks.
- Microperthite.** An intergrowth of albite with orthoclase or microcline.
- Miller indices.** Mathematical symbols for crystal faces.
- Mimetic twinning.** The tendency of twinning to raise the grade of symmetry and thus to imitate other crystals.
- Mispickel.** Synonym of arsenopyrite.
- Molecular compounds.** Compounds such as  $\text{MgSO}_4 \cdot \text{KCl} \cdot 3\text{H}_2\text{O}$  which are written as if they consist of separate molecules.
- Molybdenum minerals.** Molybdenite, wulfenite.
- Molybdates.** Salts of  $\text{H}_2\text{MoO}_4$ .
- Monochromatic.** Light of one color or approximately one wave-length.
- Monoclinic system.** The system which includes crystals with one fixed direction of symmetry.
- Moonstone.** A variety of orthoclase used as a gem.
- Morphology, crystal.** The same as geometrical crystallography.
- Mountain cork.** A porous variety of tremolite.
- Mountain leather.** A variety of tremolite resembling leather.
- Mundic.** A local miner's name for pyrite or marcasite.
- Native elements.** Elements that occur in nature uncombined.
- Negative crystal.** A cavity within a crystal of the same shape as the crystal.
- Negative elongation.** The length of a crystal is parallel to the faster ray.
- Negative, optically.** Uniaxial crystals in which  $c = \alpha$  and biaxial crystals in which the acute bisectrix is  $\alpha$ .
- Nepheline.** Same as nephelīte.
- Nepheline-syenite.** Same as nephelite-syenite.
- Nephelite-syenite.** A plutonic igneous rock composed essentially of orthoclase and nephelite.
- Nickel minerals.** Garnierite, millerite, and niccolite.
- Nicol.** A nicol prism.
- Nicol prism.** A piece of Iceland spar arranged so as to produce polarized light.
- Niobates.** Salts of  $\text{H}_3\text{NbO}_4$  and  $\text{HNbO}_4$ .
- Niobium minerals.** Columbite.
- Nitrates.** Salts of  $\text{HNO}_3$ .
- Nitratine.** Synonym of soda-niter.
- Nodular.** Consisting of a rounded lump.

**Non-metallic.** Any luster but metallic.

**Normal salt.** A salt in which all the hydrogen of the acid has been replaced by metals.

**Norite.** A gabbro in which the ferro-magnesium mineral is largely hypersthene.

**Obsidian.** A natural volcanic glass of vitreous luster.

**Obtuse bisectrix.** The line bisecting the obtuse angle between the optic axes.

**Obtuse rhombohedron.** A rhombohedron with interfacial angle less than  $90^\circ$ .

**Ocher.** A clay colored by iron oxids.

**Octahedron.** An isometric crystal with eight triangular faces at angles of  $70^\circ 32'$ .

**Octahedral cleavage.** Cleavage in four directions parallel to the faces of an octahedron.

**Omphacite.** A bright green variety of diopside occurring in eclogites.

**Onyx.** A banded variety of chalcedony.

**Onyx marble.** A banded variety of calcite or aragonite.

**Onyx, Mexican.** The same as onyx marble.

**Oölite.** A rock made up of minute spheres.

**Oölitic.** Made up of minute spheres.

**Opalescence.** The peculiar milkiness seen in opal.

**Opalized wood.** Wood replaced by opal.

**Open forms.** Crystal forms that do not enclose space of themselves.

**Opicalcite.** A serpentine veined or mottled with calcite, dolomite or magnesite.

**Optical anomalies.** Abnormalities in the optical properties.

**Optical character.** The designation as to whether optically positive or optically negative.

**Optical constants.** The indices of refraction, axial angle, extinction angle, etc.

**Optical orientation.** The position of  $\alpha$ ,  $\beta$ , and  $\gamma$  with respect to the axes of reference,  $a$ ,  $b$ , and  $c$ .

**Optic axes.** Two directions normal to the circular sections of the indicatrix for biaxial crystals.

**Optic axis.** The direction of the  $c$ -axis in uniaxial crystals.

**Optics, crystal.** The subject which treats of the transmission of light in crystals.

**Ordinary ray.** In doubly-refracting crystals the ray which produces the stationary image.

**Organic deposits.** Rocks and other deposits formed by the remains of organisms.

**Oriental amethyst.** A purple variety of corundum.

- Oriental emerald.** A green variety of corundum.
- Oriental sapphire.** The true sapphire, a variety of corundum.
- Oriental ruby.** The true ruby, a variety of corundum.
- Oriental topaz.** A yellow variety of corundum.
- Orientation, optical.** The position of the indicatrix axes  $\alpha$ ,  $\beta$ , and  $\gamma$  with respect to the axes of reference  $a$ ,  $b$ ,  $c$ .
- Orient, to, a crystal.** Is to set up with the axes of reference in their conventional position.
- Ortho-axis.** The  $b$ -axis in the monoclinic system.
- Orthodome.** The forms  $\{h0l\}$  and  $\{h0\bar{l}\}$  in the monoclinic system.
- Orthographic drawing.** A drawing made by perpendicular projectors.
- Orthopinacoid.** The form  $\{100\}$  in the monoclinic system.
- Orthorhombic system.** The system which includes crystals with three fixed directions of symmetry.
- Orthosilicates.** Salts of  $H_4SiO_4$ , the normal silicic acid.
- Oxids.** Compounds of elements with oxygen.
- Oxy-chlorid.** A compound of the type  $R_2OCl$  or  $R_2O \cdot RCl$ .
- Oxy-salt.** Ordinary salts as distinguished from sulfo-salts.
- Oxy-sulfid.** A compound of the type  $R_4OS$  or  $R_2O \cdot R_2S$ .
- Paragenesis.** The association of minerals with special reference to their occurrence and origin.
- Paragenetic varieties.** Varieties based upon mode of occurrence and origin.
- Parallel growth.** Two or more crystals with corresponding faces parallel.
- Parameters.** The intercepts of the unit face on the axes of reference.
- Paramorph.** The pseudomorph of one dimorphous mineral after another.
- Parting.** A separation caused by molecular disturbance such as twinning.
- Peacock copper.** Synonym of chalcopyrite.
- Pearl-spar.** A synonym of dolomite.
- Pearly luster.** The luster due to continued reflection from parallel plates.
- Pedal class.** The class without any symmetry.
- Pedion.** A form consisting of a single face.
- Pegmatites.** Coarse vein-like deposits occurring in plutonic igneous rocks; especially granite.
- Pentagonal dodecahedron.** Another name for the pyritohedron.
- Percussion-figure.** A six-rayed star developed on the micas by a sharp blow.
- Pericline.** A variety of albite elongated in the direction of the  $b$ -axis.
- Peridot.** The gem variety of olivine.
- Peridotite.** A plutonic igneous rock consisting essentially of olivine and some pyroxene.
- Perthite.** An intergrowth of albite with orthoclase or microcline.
- Petrifaction.** The replacement of fossils by mineral substances.

**Petrography.** The science treating of rocks, especially from the descriptive side.

**Petrographic microscope.** The same as polarizing microscope.

**Petrographic province.** A region in which the igneous rocks are supposed to have a common origin.

**Petrology.** The study of rocks from a broad standpoint.

**Phantom crystal.** A crystal in which an earlier stage of crystallization is marked in some way.

**Phenocryst.** Crystals scattered through a fine ground-mass and formed before the ground-mass.

**Phonolite.** A volcanic rock composed essentially of orthoclase and nephelite.

**Phosphate rock.** An impure massive calcium phosphate.

**Phosphorite.** Practically a synonym of phosphate rock.

**Picotite.** A chrome-bearing variety of spinel.

**Pinacoid.** A form consisting of two parallel faces.

**Pinacoidal class.** The class with a center of symmetry.

**Pisolitic.** Made up of spheres about the size of buck-shot.

**Pitch-blende.** A synonym of uraninite.

**Placers.** Stream deposits of sand and gravel.

**Plagioclase.** A group of soda-lime feldspars.

**Plaster tablets.** Thin rectangular plates used as a blowpipe support.

**Pleochroism.** The property of absorbing different kinds of light in different directions.

**Pleonaste.** An iron-bearing variety of spinel.

**Plumose.** Feather-like.

**Plutonic rocks.** Deep-seated igneous rocks.

**Poikilitic.** A term referring to inclusions irregularly arranged through a crystal.

**Polar edges.** Polar edges are those that intersect the  $c$ -axis.

**Polarized light.** Light in which the vibrations are in one plane.

**Polarizer.** The lower nicol.

**Pole.** The projection of a crystal face on a sphere made by a radius normal to the face.

**Polyhedron.** A general name for a solid bounded by plane faces.

**Polymorphism.** The occurrence of a substance in two or more modifications which differ in crystallization.

**Polysynthetic twin.** A twin made up of three or more parts in which the same face serves as twin-plane.

**Positive elongation.** The length of the crystal is parallel to the slower ray.

**Positive, optically.** Uniaxial crystals in which  $c = \gamma$  and biaxial crystals in which the acute bisectrix is  $\gamma$ .

**Potash.**  $K_2O$ .

**Potassium minerals.** Alunite, biotite, carnallite, kainite, lepidolite, leucite, microcline, muscovite, orthoclase, sylvite.

- Porphyry.** An igneous rock with porphyritic texture.
- Porphyritic.** With crystals set in a fine ground-mass.
- Precious opal.** A variety of opal with a play of colors.
- Primitive circle.** The great circle in the plane of projection (stereographic projection).
- Primitive form.** A form from which other forms may be derived.
- Principal axis.** The *c*-axis in tetragonal and hexagonal crystals.
- Prism.** An open form with faces all in one zone.
- Prismatic class.** The class with the symmetry  $A_2P.C$ .
- Prismatic habit.** Applied to crystals that are elongated in one direction.
- Projection, gnomonic.** A projection made on a plane tangent to a sphere.
- Projection, linear.** A projection formed by crystallographic planes shifted so that they cut the unit length of the *c*-axis on a horizontal plane.
- Projection, stereographic.** A projection made on a plane through the center of a sphere by projectors from the south pole.
- Pseudo-hexagonal.** Orthorhombic or monoclinic crystals which simulate crystals of the hexagonal system.
- Pseudomorph.** A mineral with the crystal form of another mineral.
- Pyknometer.** A small flask for specific gravity determinations.
- Pyramid.** An open form consisting of several faces meeting in a point.
- Pyramidal habit.** With the general shape of a pyramid.
- Pyrites.** Synonym of pyrite. Also used for other minerals, *e.g.*, copper pyrites.
- Pyritohedron.** The form  $\{hk0\}$  in the isometric diploid class.
- Pyroclastic.** Made up of fragmental volcanic products.
- Pyroelectric.** The property of developing electricity on heating or cooling.
- Pyrognostic tests.** The same as blow-pipe tests.
- Pyrope.** A sub-species of garnet containing Mg and Al.
- Pyroxene.** A name sometimes used for diopside and augite together.
- Pyroxene group.** A group of metasilicate minerals.
- Pyroxenite.** A plutonic igneous rock composed essentially of some pyroxene.
- Quarter-undulation.** Refers to one-fourth of a wave-length for sodium light.
- Quartzite.** A metamorphic rock made up of firmly cemented quartz grains.
- Quartz-wedge.** A wedge-shaped slice of quartz used in optical work.
- Quicksilver.** A synonym of mercury.
- R.** A general symbol standing for some metal as  $RCO_3$ .
- Radical.** A group of elements such as  $NH_4$  or  $SO_4$ .
- Radium.** An element found in uraninite.
- Rare-earth metals.** Cerium, didymium, erbium, lanthanum, thorium and yttrium.

- Rational indices.** The indices of crystal faces are rational numbers, usually simple numbers below 6.
- Reduction.** The taking away of oxygen or the change to a lower state of oxidation.
- Reduction color tests.** Tests made with  $\text{NaPO}_3$  beads and tin.
- Reflection goniometer.** An instrument for measuring interfacial or coördinate angles.
- Reflection, total.** The turning back of light rays when the critical angle is exceeded.
- Refraction.** The bending of light rays when passing from one medium into another.
- Refraction, index of.** A number to express the amount of refraction.
- Refractometer.** An instrument for determining the index of refraction.
- Regular system.** Same as the isometric system.
- Relief.** The appearance of a substance as depending upon its index of refraction and that of the substance in which it is embedded.
- Reniform.** Kidney-shaped.
- Replacement.** (1) Substitution of a rock or vein by mineral matter. (2) The substitution of an element or radical by other element or radical.
- Resinous.** The luster of resin.
- Reticulate.** Made up of a net-work.
- Rhombic bipyramid.** A bipyramid with rhombic cross-section.
- Rhombic prism.** A prism with rhombic cross-section.
- Rhombic system.** Same as orthorhombic system.
- Rhombohedral class.** The crystal class with the symmetry  $P_3$ .
- Rhombohedron.** A six-faced form resembling a distorted cube.
- Rhyolite.** A volcanic igneous rock composed essentially of quartz and orthoclase with more or less glass.
- Rock.** An essential part of the earth's crust.
- Rock crystal.** The clear transparent variety of quartz.
- Rock salt.** Synonym of halite.
- Rubellite.** The pink or red variety of tourmaline.
- Ruby.** The red transparent variety of corundum.
- Ruby copper.** Synonym of cuprite.
- Ruby silver.** A group name including pyrargyrite and proustite.
- Rutilated quartz.** Quartz penetrated by needles of rutile.
- Salt.** Synonym of halite.
- Salt of phosphorus.** Sodium ammonium phosphate, a reagent used in blow-pipe analysis.
- Salts, acid.** Salts in which only part of the hydrogen of the acid has been replaced by metals.
- Salts, basic.** Salts in which only part of the hydroxyl of the base has been replaced by acid radicals.

**Salts, normal.** Salts in which hydrogen of acid and hydroxyl of base have been replaced.

**Sandstone.** A sedimentary rock composed of consolidated sand.

**Sanidine.** A glassy transparent orthoclase occurring in volcanic rocks.

**Sapphire.** A blue transparent variety of corundum.

**Satin-spar.** A fibrous variety of gypsum.

**Scalenoedron.** A twelve-faced form with the symmetry  $A_3, 3A_2, 3P$  and with alternate interfacial angles equal.

**Scapolite.** A synonym of wernerite.

**Schiller.** A bronze-like reflection caused by inclusions.

**Schist.** A metamorphic rock which splits into thin layers.

**Schistose.** Splitting into thin layers.

**Schorl.** An old name for tourmaline.

**Secondary.** Minerals formed subsequent to those of the main rock mass are said to be secondary.

**Sectile.** Capable of being cut by a knife but not flattened under a hammer.

**Sedimentary.** Laid down in water.

**Selenite.** The cleavable variety of gypsum.

**Selenite plate.** A plate of selenite which gives a purplish-red interference color of the first order with crossed nicols.

**Semi-opal.** Common opal as distinguished from precious and fire opal.

**Sensitive tint.** The purple interference color given by a selenite plate (red of the first order).

**Sericite.** A silvery variety of muscovite, usually secondary.

**Serpentine (mineral).** The mineral.

**Serpentine (rock).** A metamorphic rock formed from a peridotite.

**Serpentinization.** The change of peridotite to serpentine rock.

**Shale.** A clastic rock formed by the consolidation of fine aluminous sediments.

**Sill.** A dike-like igneous rock parallel to sedimentary beds.

**Silver glance.** Synonym of argentite.

**Silver minerals.** Argentite, cerargyrite, polybasite, proustite, pyrargyrite, silver, stephanite, sylvanite.

**Skeleton crystals.** Hollow or imperfectly developed crystals formed by rapid crystallization.

**Slate.** Thinly cleavable fine grained metamorphic rocks formed from shales.

**Smalt.** Cobalt silicate used as a pigment.

**Smoky quartz.** A variety of quartz colored by a brownish pigment.

**Soda.** (1) Sodium carbonate, a blowpipe reagent. (2)  $Na_2O$ .

**Soapstone.** A massive talc rock.

**Sodium metaphosphate.** A reagent used in blowpipe analysis,  $NaPO_3$ .



**Sodium minerals.** Aggrite, albite, analcite, borax, cryolite, glaucophane, halite, lazurite, mirabilite, natrolite, nephelite, pectolite, sodalite, soda niter, trona, ulexite, wernerite.

**Specific gravity.** The weight of a substance compared with an equal bulk of water.

**Specular iron ore.** A synonym of hematite.

**Specularite.** A synonym of hematite.

**Spessartite.** A sub-species of garnet containing Mn and Al.

**Sphene.** A synonym of titanite.

**Sphenoid.** A form consisting of two faces not astride a plane of symmetry.

**Sphenoidal class.** The class with an axis of 2-fold symmetry.

**Stalactite.** Icicle-like crystalline aggregates.

**Stalactitic.** Referring to stalactites.

**Steatite.** A massive talc rock.

**Stereogram.** A stereographic projection of a crystal.

**Stereographic projection.** A projection made on a plane through the center of a sphere by projectors from the south pole.

**Stratified rocks.** Rocks made up of layers and usually formed in water.

**Streak.** The color of the powder of a mineral.

**Streak-plate.** A piece of unglazed porcelain for testing the streak.

**Stream-tin.** A variety of cassiterite found in the form of pebbles or sand in placers.

**Strontium minerals.** Celestite, strontianite.

**Sub-.** A prefix indicating a lower quality or degree than the normal.

**Subsilicates.** Silicates of the type  $n\text{RO} \cdot \text{SiO}_2$  ( $n > 2$ ).

**Sulfantimonates.** Salts of  $\text{H}_3\text{SbS}_4$ .

**Sulfantimonites.** Salts of  $\text{H}_3\text{SbS}_3$ .

**Sulfarsenates.** Salts of  $\text{H}_3\text{AsS}_4$ .

**Sulfarsenites.** Salts of  $\text{H}_3\text{AsS}_3$ .

**Sulfates.** Salts of  $\text{H}_2\text{SO}_4$ .

**Sulfids.** Salts of  $\text{H}_2\text{S}$  or compounds of the metals and semi-metals with S.

**Sulfo-acids.** Acids of the type  $\text{H}_3\text{AsS}_4$ ,  $\text{H}_3\text{AsS}_3$ , etc.

**Sulfo-salts.** Salts of the type  $\text{R}'_3\text{AsS}_4$ , in which O of ordinary salts has been replaced by S.

**Supplementary twinning.** Twinning by which a crystal simulates the symmetry of a crystal class with higher grade in the same system.

**Symbols of crystal faces.** Mathematical expressions for designating the position of crystal faces on coordinate axes.

**Symmetry.** The rhythmical recurrence of faces, edges; and vertices.

**Symmetry, axis of.** A line about which a crystal may be revolved so it occupies the same position in space as before.

**Symmetry, center of.** A crystal that for every face has a similar opposite parallel face has a center of symmetry.

**Symmetry, composite.** The recurrence of faces, etc., by rotation about an axis combined with reflection in a plane normal to the axis.

**Symmetry, plane of.** A plane that divides a crystal into two parts so that similar faces occur on opposite sides of the plane.

**Syenite.** A plutonic igneous rock composed principally of orthoclase.

**Synthesis, mineral.** The artificial production of minerals.

**Systems, crystal.** Crystals which have the same kind of axes of reference constitute a system.

**Symmetrical dispersion.** The dispersion which produces an interference figure with color distribution symmetrical to trace of axial plane and also to a line normal to this.

**Tabular habit.** The crystal habit due to limited growth in one direction.

**Talc-schist.** A talc rock that splits in thin layers.

**Tantalum minerals.** Columbite.

**Tarnish.** A surface layer usually caused by oxidation.

**Tellurids.** Salts of  $H_2Te$ .

**Tellurium minerals.** Calaverite, sylvanite.

**Tenonite.** Synonym of melaconite.

**Tetartohedral.** Classes in which the general form has one-fourth the number of faces of the general form of the holohedral class.

**Tetartoid.** The twelve-faced general form of the tetartoidal class.

**Tetartoidal class.** The class with the symmetry  $3A_2 \cdot 4A_2$ .

**Tetartopyramid.** The form  $\{hkl\}$  in the triclinic system.

**Tetragonal system.** The system which includes the crystal classes with a single axis of four-fold symmetry.

**Tetrahedron.** A form consisting of four equilateral triangular faces.

**Tetrahexahedron.** The twenty-four faced form  $\{hkl\}$  of the isometric system.

**Texture.** The mutual relations of the minerals in a rock.

**Thin section.** A paper-thin slice of a rock or a mineral.

**Thoria.** The oxid of thorium,  $ThO_2$ .

**Tiger's-eye.** A quartz pseudomorph after fibrous crocidolite (a soda amphibole).

**Tin minerals.** Cassiterite, stannite.

**Tin-stone.** A synonym of cassiterite.

**Tin-stone veins.** Veins intermediate between ordinary veins and pegmatites.

**Titanium minerals.** Ilmenite, rutile, titanite.

**Total reflection.** The turning back of light rays when the critical angle is exceeded.

**Touch stone.** A black variety of chalcedony used for testing the streak of gold and other metals.

**Trachyte.** A volcanic igneous rock composed principally of orthoclase.

- Trap.** A dense black igneous rock, usually either basalt or diabase.
- Trapezohedron, hexagonal.** The 12-faced form with the symmetry  $A_3 \cdot 6A_2$ .
- Trapezohedron, isometric.** The 24-faced form  $\{hkk\}$  in the hexoctahedral, diploidal, and gyroidal classes of the isometric system.
- Trapezohedron, tetragonal.** The 8-faced form with the symmetry  $A_4 \cdot 4A_2$ .
- Trapezohedron, trigonal.** The 6-faced form with the symmetry  $A_3 \cdot 3A_2$ .
- Travertine.** A banded calcium carbonate rock formed from water solution.
- Triclinic system.** Includes the crystal classes without any fixed direction of symmetry.
- Trilling.** A twin crystal with three individuals or parts.
- Trimorphism.** The same substance in three different modifications.
- Trisectahedron.** An isometric form of 24 faces with the symbol  $\{hll\}$ .
- Tristetrahedron.** An isometric form of 12 faces with symbol  $\{hkk\}$ .
- Troostite.** A variety of willemite containing manganese.
- Truncation.** The modification of an edge by a face that makes equal angles with adjacent faces.
- Tufa, calcareous.** A porous deposit of calcium carbonate formed by water solution.
- Tuff.** A fragmental volcanic rock.
- Tungstates.** Salts of  $H_2WO_4$ .
- Tungsten minerals.** Hübnerite, scheelite, wolframite.
- Turkey-fat ore.** A yellow variety of smithsonite containing cadmium.
- Turmeric paper.** Paper used for testing borates and zirconium.
- Twin-axis.** The line about which one part of the twin has apparently been revolved.
- Twin-crystals.** Crystals in which one part is in reversed position with respect to the other.
- Twin-plane.** A plane normal to the twin-axis.
- Type symbols.** The general symbols  $hkl$ ,  $hk0$ , etc., for crystal faces.
- Ultrabasic rocks.** Igneous rocks with less than about 35 per cent. of silica.
- Uranium minerals.** Uraninite.
- Unit bipyramid.** The form  $\{111\}$ .
- Unit form.** The form  $\{111\}$  or  $\{10\bar{1}1\}$ .
- Unit prism.** The form  $\{110\}$ .
- Unit pyramid.** The form  $\{111\}$ .
- Unit series of bipyramids.** The forms  $\{hhl\}$ .
- Unisilicates.** Same as orthosilicates,  $R_2''SiO_4 = 2RO \cdot SiO_2$ .
- Uralite.** An actinolite pseudomorph after, or alteration of, augite.
- Uralitization.** The alteration involved in the formation of uralite.
- Uvarovite.** A sub-species of garnet containing Ca and Cr.

**Vanadates.** Salts of  $H_2VO_4$ .

**Vanadium minerals.** Vanadinite.

**Veins.** Narrow mineral masses formed by water solutions usually in fissures.

**Vibration directions.** The same as extinction directions.

**Vicinal faces.** Crystal faces with high indices adjoining or replacing faces with simple indices.

**Vitreous luster.** A luster like that of ordinary glass or quartz.

**Volcanic ash.** A fine fragmental volcanic deposit.

**Volcanic breccia.** A coarse fragmental volcanic deposit.

**Volcanic rocks.** Igneous rocks which solidified at or near the earth's surface.

**Volcanic tuff.** A more or less consolidated fragmental volcanic rock.

**Vug.** A cavity in a rock or vein usually lined with crystals.

**Wave-length.** The distance wave-motion of light is transmitted during one vibration.

**Weathering.** Superficial alteration.

**Weiss symbols.** Crystallographic symbols involving intercepts on the axes of reference.

**Westphal-balance.** A convenient apparatus for determining the specific gravity of a liquid.

**Wood-opal.** A variety of opal formed by the replacement of wood.

**Wood silicified.** Chalcedony or opal formed by the replacement of wood.

**Yellow ocher.** A clay colored by limonite.

**Zeolites.** A group of hydrous silicates.

**Zinc blende.** A synonym of sphalerite.

**Zinc minerals.** Calamine, franklinite, hydrozincite, smithsonite, sphalerite, willemite, zincite.

**Zinc white.** Artificial zinc oxid used as paint.

**Zirconia.** Oxid of zirconium,  $ZrO_2$ .

**Zirconium minerals.** Zircon.

**Zonal relations.** The mathematical relations of face symbols and zone symbols.

**Zone.** A belt of planes on a crystal the intersection edges of which are parallel.

**Zone axis.** The direction of the intersection edges of the faces of a zone.

**Zone circle.** A great circle containing the poles of all the crystal faces in a zone.

**Zone symbol.** A symbol written thus  $[uvw]$  to distinguish it from a face or form symbol.



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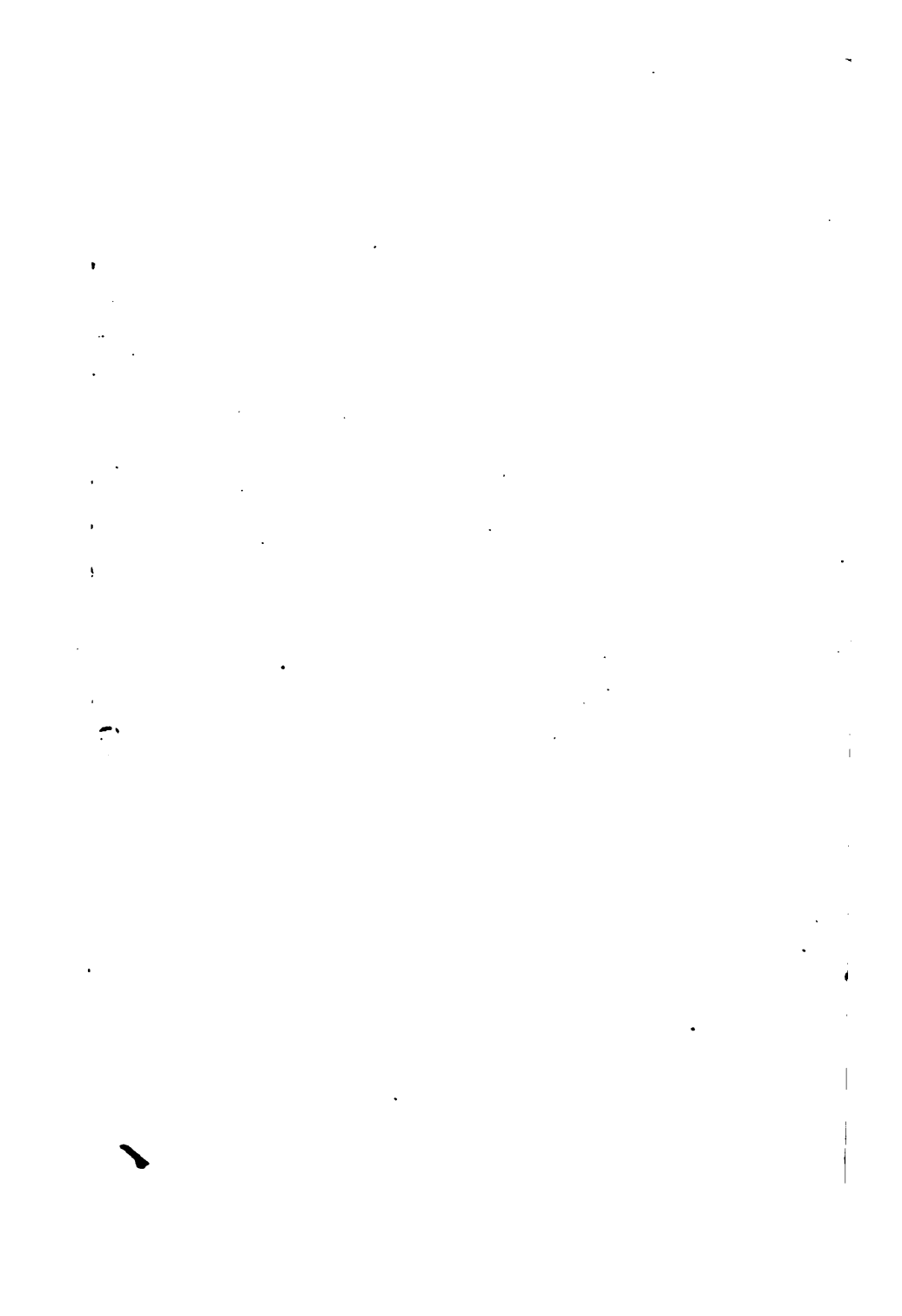
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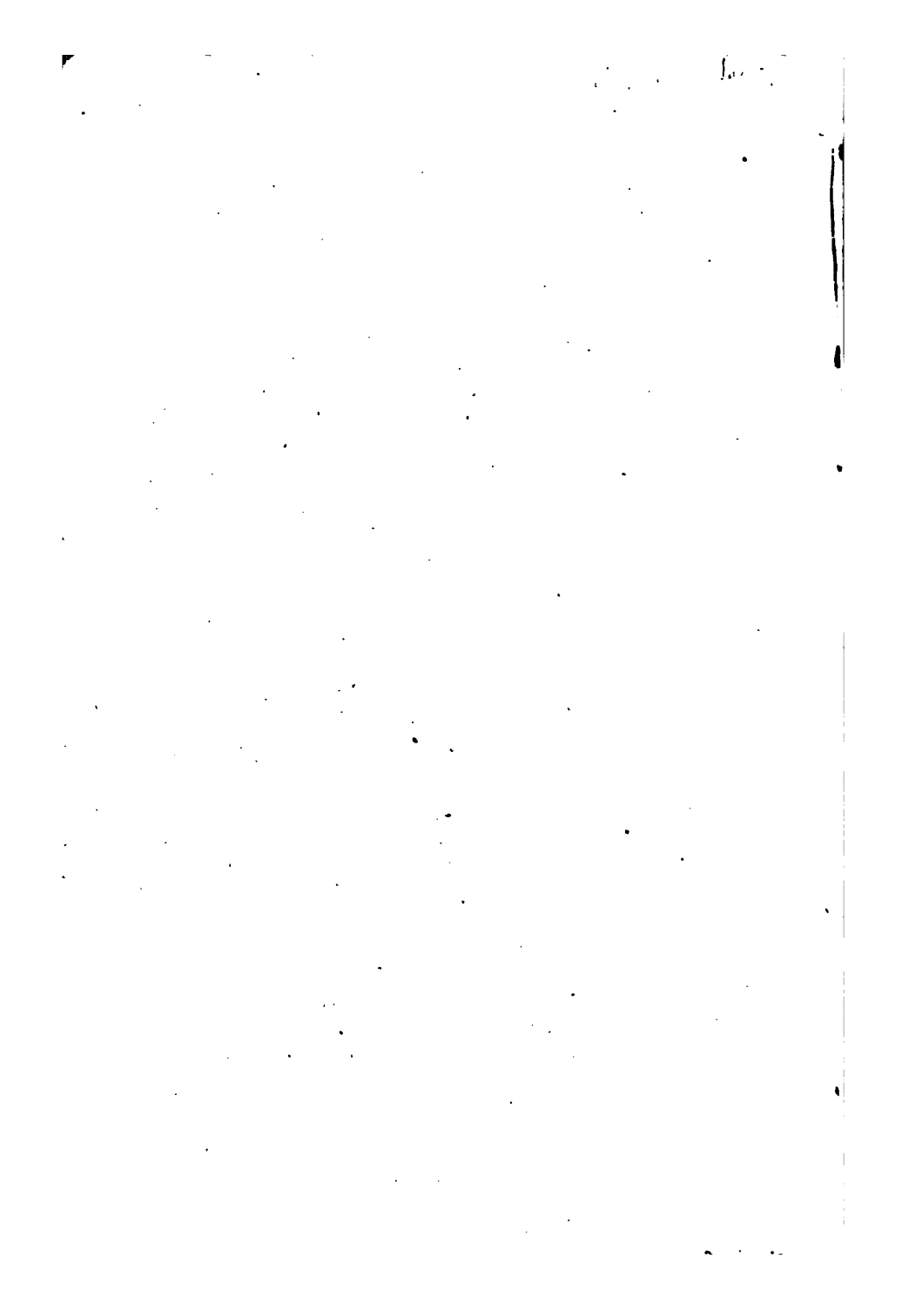
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